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Mortality and Growth Responses of Juvenile Pines and Hardwoods to Various Fire Intensities.

Thomas Alexander Greene
Louisiana State University and Agricultural & Mechanical College

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Mortality and growth responses of juvenile pines and hardwoods to various fire intensities

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The Louisiana State University and Agricultural and Mechanical Col., 1987

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MORTALITY AND GROWTH RESPONSES OF JUVENILE PINES AND HARDWOODS TO VARIOUS FIRE INTENSITIES

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The School of Forestry, Wildlife, and Fisheries

by
Thomas Alexander Greene
B.S., Texas A&M University, 1980
M.S., Texas A&M University, 1983
May 1987

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To JFD, who knew the truth.

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February 12, 1987

Thomas A. Greene
School of Forestry, Wildlife,
and Fisheries
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Dear Mr. Greene:

I recently received your request dated February 3, 1987 to reprint Figures 1 and 2 and Table 1 from "A Propane-Fueled Fire Simulator" by you, Charles l. Shilling, and Vernon S. Compton which appeared in the December 1986 Journal of Forestry. The Society of American Foresters grants this permission for use in your dissertation which is to be published by University Microfilms, Inc.

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ABSTRACT

Prescribed burning for hardwood control in young southern pine stands has been limited by inability to predict the safety and efficacy of burns of specific intensities. In this study I quantified the effects of various fire intensity levels on girdling, scarring, and subsequent-year growth response of loblolly pine (*Pinus taeda* L.), water oak (*Quercus nigra* L.) and sweetgum (*Liquidambar styraciflua* L.) saplings between 3 and 10 cm diameter at ground line (dgl).

Two hundred saplings of each species in four dgl classes were treated at five fire intensity levels, 0, 36, 64, 80, and 98 kJ/s/m, with a propane-fueled backfire simulator during winter 1985. The following variables were measured and tested for inclusion in logistic regression models of probability of girdling: temperature exposure (area under the temperature x time curve, $^{o}C*s$) at four locations around the base of the trees, maximum temperature outside bark, duration of lethal temperatures, dgl, diameter at breast height (dbh), bark thickness, bark moisture content, air temperature, bark temperature, and relative humidity.

Mean temperature exposures varied between 4,960 and 60,460 $^{o}C*s$, mean temperature maxima ranged from 139^{o}C to 718^{o}C, and mean lethal temperature durations varied from 141 s to 275 s, depending on propane flow rate and thermocouple position relative to wind direction.
Of 200 trees in each species, 10 loblolly pines were girdled (out of 35

scarred), 98 water oaks were girdled (143 scarred), and 95 sweetgums were girdled (142 scarred).

Logistic regression models I developed from these data to predict girdling in 3-10 cm dgl stands of loblolly pine, water oak, and sweetgum by backfires with fire intensities of 0-98 kJ/s/m are:

Loblolly pine:

$$P_p = [1+e^{-(5.1302-0.4361(dgl)+0.00021(mte))}]^{-1}$$

Water oak:

$$P_o = [1+e^{-(-0.9480-0.0653(dgl)+0.00019(mte))}]^{-1}$$

Sweetgum:

$$P_g = [1+e^{-(-2.3597-0.0901(dgl)+0.00030(mte))}]^{-1}$$

where:

$P_{p,o,g}$ = Probability that an individual stem of loblolly pine (P_p), water oak (P_o), or sweetgum (P_g) will be girdled;

dgl = stem diameter (mm), 3 cm above mineral soil;

mte = mean temperature exposure based on four thermocouple measurements at the base of the stem, $^oC*s$.

INTRODUCTION

Prescribed fire is often used in the southern United States to suppress hardwoods in stands of southern pines, particularly loblolly pine (*Pinus taeda* L.), slash pine (*P. elliottii* Engelm.), shortleaf pine (*P. echinata* Mill.), and longleaf pine (*P. palustris* Mill.). However, its use in forestry is limited by the size and degree of fire resistance of the crop species. Hence, chemicals and mechanical treatments must often be used with prescribed fire in pine management systems to control competing hardwoods while the pines are too small to survive a fire.

The low cost of prescribed fire as compared with herbicide application and mechanical hardwood control provides incentive to burn pine stands as early as possible to keep stand establishment costs at an acceptable level. Several authors have set minimum stand sizes or ages at which this first burn may be applied in southern pine stands, and most agree that a diameter at breast height (dbh) of 8-10 cm and a height of 1.5-4.0 m is necessary before prescribed burning for hardwood control is safe (Bickford and Curry 1943, Crow and Shilling 1980, Ferguson 1961, McCulley 1950).[1] Age at which this size is reached depends on site and species but is usually between 8 and 15 years (McCulley 1950, Crow and Shilling 1983).

Recent speculation and studies have suggested that these size limits could be reduced (McNab 1977, Waldrop and Lloyd 1987, Johansen

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and Wade 1987), but little information detailing the effects of fire of a given intensity upon trees of a given size is currently available. Without quantitative knowledge of the effects of fire on young stands it will be difficult to use prescribed burning to its maximum potential as a management tool in southern pine forestry.

This study was performed to quantify the effects of low intensity backfires on three common southern tree species, one of which, loblolly pine, is the most commercially important timber species in the South, and two of which, water oak (*Quercus nigra* L.) and sweetgum (*Liquidambar styraciflua* L.), are common weed species on pine sites. Water oak and sweetgum are frequently the targets of hardwood control efforts, including prescribed burning. Objectives of this study were:

1. to determine the effects of various fire intensities on mortality and growth of loblolly pine, water oak, and sweetgum saplings between 3 and 10 cm diameter at ground line (dgl), and

2. to construct predictive regression models of mortality for these species and sizes of trees based on fire parameters and dgl.

LITERATURE REVIEW

Fire Intensity Measurement

The concept of fire intensity has been approached from two points of view, one based on the amount of heat produced by a fire, the other a more empirical method based on the temperature and duration of flames. Byram (1959) defined intensity as I = Hwr where:

I = intensity, kJ/s/m (kilojoules per second per meter),

H = heat yield of fuel, kJ/kg (kilojoules per kilogram),

w = weight of available fuel, kg/m^2 (kilograms per square meter), and

r = rate of spread of fire front, m/s (meters per second).

This equation yields an intensity value which approximates the rate of release of heat energy per unit length of fire front. Byram's fire intensity can also be estimated empirically from flame length (Byram 1959).

Alexander (1982) asserted that "prediction of the biological and ecological effects of fire must ultimately be linked to quantitative characteristics of fire behavior" and advocated the use of Byram's fire intensity equation. However, he pointed out that estimating the values of H, w, and r is often difficult. For example, the weight of fuel actually oxidized will be less than the weight loss in the fuel bed because of incomplete combustion. Also, fuel beds are usually heterogeneous, allowing H, w, and r to vary within small areas.

Finally, Byram's intensity does not take into account whether a fire is a headfire or a backfire, so a slow backfire with high fuel consumption may have the same I-value as a fast headfire with low fuel consumption, though these may have very different effects on the vegetation. Hare (1961) concluded that backfires may be more damaging to woody plant stems. Overall they are cooler than headfires, yet they may be hotter very close to the ground, and they move more slowly. In an attempt to circumvent this last difficulty, McArthur and Cheney (1966) suggested that "burnout time" be reported along with intensity to give an indication of the duration of high temperature at a given point.

Byram's intensity is also a good predictor of height of crown scorch in forest fires (Van Wagner 1973). Apparently a measure of the total amount of heat produced suffices to predict the damage to unprotected plant parts, but an indication of duration must be included to predict damage to insulated plant parts such as bole cambium.

Maximum fire temperature is a commonly reported variable in ecological studies and is one of the most easily measured, since chemicals with specific melting points, formed either into tablets or in crayon form, are available and may be placed at any point in a fire to determine maximum temperature reached (Whittaker 1961, Williamson and Black 1981). However, maximum temperature by itself is a poor indicator of the effect a fire will have on a stem because the amount of heat conducted through material depends not only on the temperature differential between source and sink, but also on the length of time the differential is maintained. The greater the differential the faster will be the heat flow, but the duration of the temperature difference is important also, because as soon as the heat source is removed reverse flow begins and the substance cools. Thus, a brief hot pulse may not damage a stem while the prolonged occurrence of temperatures slightly higher than lethal temperature may result in cambial death.

Flame temperature and duration of exposure may be combined to give a more accurate picture of fire intensity (Davis 1959). These variables are fairly easily measured in a prescribed burn and directly influence vegetation response to burning. For example, the amount of damage sustained by loblolly pines in a prescribed burn depended on flame temperature and duration of exposure as well as bark thickness (Chapman 1942). Ferguson et al. (1960) reported that extended exposure to a cool fire caused serious basal wounds on mature loblolly and shortleaf pines.

Nelson (1952) tested heat tolerance of pine needles and found that as temperature increased from 54.4^{o}C to 63.8^{o}C lethal exposure time decreased from 3 min to near 0 min, indicating an exponential relationship of lethal exposure time with temperature. Rasmussen (1981) found that the integral of the temperature x time relationship predicted top-kill of huisache (Acacia farnesiana (L.) Willd.) better than maximum temperature alone under artificial burning conditions.

Davis and Martin (1960) used steel-sheathed chromel-alumel thermocouples attached to milliammeters to record time-temperature relationships of fires in gallberry-palmetto fuels in Georgia. They presented graphs of temperature as a function of time at two heights during a headfire and a backfire. Tunstall et al. (1976) studied the distribution of temperatures around asbestos-covered cylinders in grass fires and reported time-temperature curves for leeward sides, windward sides, and flanks of the cylinders. Gill (1974) modeled flames around trees in the presence of wind with a Meker burner, small metal rods, and a fan. He found that flames reached higher and were hotter on the lee side of the rod and discussed the idea that wind causes one-sided scarring of tree boles, where girdling might occur on relatively calm days because of more uniform heating.

Temperatures measured during natural fires exhibit a broad range and are heavily influenced by fuel type and amount and by burning conditions, as well as by the method and position of measurement. In heavy longleaf pine fuels Hare (1961) reported maximum temperatures of near 850°C near tree boles and 700°C in the open (away from trees). He recorded the highest temperatures 1 m above the ground on the lee side of the trees. Average maximum temperatures in backfires in pine litter were 523°C and in headfires 618°C, measured at ground line, and did not differ between windward and leeward sides of trees.

Temperatures decreased with height much more quickly in backfires than in headfires. Lindenmuth and Byram (1948) reported thermocouple reading maxima of 260°C at 13 cm above the ground in headfires in southern pine fuels and 370°C in backfires at the same height. Davis and Martin (1960) reported maxima at 30 cm above the ground in gallberry-palmetto fuel in Georgia to be near 870°C in headfires and about 310°C in backfires. Williamson and Black (1981) reported temperatures at 50 cm above the soil surface under longleaf pine to be near 280°C during experimental fires.

In heath fires in Scotland, Whittaker (1961) recorded temperature maxima between 440°C and 715°C at ground level. Tunstall et al. (1976) recorded average maxima at 40 cm above the ground of 250°C on the leeward side of 27-cm-diameter cylinders and 140°C on the windward side of the cylinders in heavy grass fuels.

Methods of Heat Application

Experimenters have devised various methods of applying controlled amounts of heat to plants. Nelson (1952) used hot water baths to test temperature tolerance of conifer leaves. Baker (1929) applied infrared radiation to conifer seedlings in an attempt to simulate insolation damage. Kayll (1968) tested the resistance of seedlings of several tree species to hot air and concluded that as temperature increases from optimum to lethal, survivable exposure time decreases rapidly, then slowly approaches zero. Sackett and Ward (1972) developed a mobile heat applicator to apply radiative heat to tree stems.

Several methods of applying flame to plants have been reported. A propane torch was used to test the degree of insulation afforded the cambium layer of stems by bark; minimum lethal flame duration increased exponentially with bark thicknesses up to 1.25 cm (Southern Forest Experiment Station 1959, Hare 1965a). Kayll (1963) also used a propane torch to heat eastern white pine (_P. strobus_ L.) while monitoring external bark temperature and temperature of the cambium layer. Applying flame with kerosene-soaked wicks was tried with some success (Southern Forest Experiment Station 1960, Hare 1965b). Wright and Klemmedson (1965) devised a portable combustion chamber to test the effects of various intensities of fire on individual grass plants. They regulated maximum temperature by varying the amount of shredded paper fuel in the chamber. Britton and Wright (1979) reported on a later, propane-fueled version of the portable burner and published temperature x time curves for various flame durations. Rasmussen (1981) modified the propane-fueled burner to facilitate its use on small trees.

The Role of Bark

McCarthy and Sims (1935) asserted that bark thickness and tree height are the most important characteristics influencing resistance to fire-caused top-kill in most woody plants. As trees grow, their bark becomes thicker (Nickles et al. 1981), so diameter and age are also closely correlated to fire resistance. Little and Moore (1945) burned oak-pine stands in New Jersey and found that percent mortality was inversely related to dbh and that pines were generally more resistant than oaks. Hardwood stems less than 2.5 cm dbh were more susceptible to top-kill than those between 3 and 10 cm dbh during a slash burn in Virginia, though the trees with smaller diameters were more likely to sprout following the fire (Elliott and Pomeroy 1948). McCarthy and Sims (1935) observed a direct, nonlinear relationship between diameters of Appalachian hardwoods up to 43 cm dbh and fire resistance to wildfires of various intensities. Ferguson (1961) documented a direct relationship between stem diameter and fire resistance in a pine-hardwood stand in Texas.

Bark thickness has been measured directly and correlated with ability to survive fire. Spalt and Reifsnyder (1961) reviewed the research on the relationship of bark characteristics to fire resistance and concluded that "except for thickness, no physical characteristic of bark has been related to thermal properties." Nickles et al. (1981) found a high correlation between bark thickness at ground line and survival of young shortleaf pines in Oklahoma. Bark thickness was also highly correlated with ground-line diameter. McNab (1977) observed the effects of a low-intensity wildfire in a dense, uneven-aged stand of young loblolly pines and also was able to correlate bark thickness with tree survival. He suggested the possibility of using fire as a precommercial thinning treatment for loblolly pine and stressed the need for more research into the relationship between tree size and mortality on burned areas.

Bark characteristics other than thickness apparently also have a role in fire resistance. Kaufert (1933) raised the possibility that bark texture may have an influence on fire resistance of bottomland hardwood species. Bark of sweetgum, holly (*Ilex* sp.), and cherry (*Prunus* sp.) transmitted heat twice as rapidly as bark of the same thickness from southern pines (*Pinus* spp.), baldcypress [*Taxodium distichum* (L.) Rich.], and southern magnolia (*Magnolia grandiflora* L.) (Southern Forest Experiment Station 1960). Hare (1961) suggested that the content of cork in the bark may influence its insulating qualities and that bark with a high moisture content would transmit heat faster than a drier bark.

Fire Damage

Types of injury. Various aspects of fire-induced tree injury have been investigated. Crown scorch (needle discoloration and death caused by high temperature) is the most often-cited factor in conifer mortality, while girdling and scarring of the lower stem is the most widely cited mechanism of fire damage to hardwoods in the southeastern United States. This dichotomy reflects the different strategies which have evolved by which plants survive surface fires. Southern pines avoid shoot death in low-intensity fires by virtue of their thick insulating bark (Chapman 1942, Chang 1954) while most hardwoods in the same communities tolerate more stem damage, and sprout vigorously from basal buds when girdled or severely scarred by fire.

Crown scorch. As trees grow taller they are less likely to suffer crown scorch. Bickford and Curry (1943) recommended that stands of slash pine not be burned until they reach 1.5 m in height to avoid scorch. Allen (1960) measured crown scorch in a severe summer fire and found a direct correlation of survival of loblolly pine with increasing tree height. Gruschow (1952) compared the effects of winter backfires and headfires on slash pine and found that headfires caused significant crown scorch and reduced subsequent growth of the pines, while backfires did not affect growth. A moderate degree of crown scorch may increase subsequent growth rates of loblolly pine by removing inefficient lower branches; however, severe scorch can kill even moderately large trees (Villarrubia and Chambers 1978). Johansen (1975) reported a similar relationship between scorch and growth of slash pine.

Several workers have studied the effects of crown scorch on the southern pines. Waldrop and Van Lear (1984) reported that moderate scorch did not affect growth or survival of dominant and codominant pole-size loblolly pines in unthinned stands, but that 100% scorch resulted in 20-30% mortality in the lower crown classes. Villarrubia and Chambers (1978) found that slight crown scorch (less than 15%) had a beneficial effect on diameter growth of loblolly pine, while more severe scorch caused growth losses and mortality. These negative effects were disproportionately larger in the lower crown classes. Tree size was positively correlated with survival after a summer fire in 13-20 cm dbh loblolly pines (Allen 1960). Cooper and Altobellis (1969) cited crown scorch as the major cause of mortality in a young loblolly pine stand they burned in late May, although at least one tree was apparently girdled by a backfire. McNab (1977) suggested the possibility of using fire to selectively remove smaller loblolly pines from dense young stands after he observed crown scorch and mortality resulting from a low intensity wild backfire in which mostly smaller, weaker trees died. Chambers et al. (1986) reviewed the literature on fire damage to conifers and listed crown scorch and consumption as the most prominent symptoms of fire injury. Wade and Johansen (1986) concluded after reviewing the literature on crown scorch and stem damage to pines that most damage which occurs during prescribed burning could be avoided by more judicious selection of burning conditions.

Other species of southern pines, notably slash pine, have also been the subjects of numerous studies to evaluate fire-induced damage and mortality. Gruschow (1952) found that degree of crown scorch was negatively correlated with survival and growth of young slash pine after winter headfires. Mann and Whittaker (1955) obtained similar results with 4-year-old planted slash pines and noted that small trees (less than 1.2 m tall) which suffered more than 75% crown scorch were most likely to die. McCulley (1950) recorded diameter and height growth losses after burning as a function of degree of crown scorch in 3-18 cm dbh slash pines. He concluded that all levels of crown scorch produced growth losses for at least 3 years, and that even trees not visibly damaged by the fire suffered growth losses if they were below 8 cm dbh. However, Johansen (1975) reported growth increases in slightly (less than 15%) scorched slash pines. McCulley (1950) also pointed out the importance of differentiating between crown scorch (where needles are killed but apical buds are probably not) and crown consumption, where the needles are consumed in the flames and bud damage is much more likely. In his study, McCulley found that trees which suffered partial crown consumption were much more likely to die than those which were only scorched. Storey and Merkel (1960) found that for slash and longleaf pines the percent of crown consumed was a better predictor of mortality than scorch, because the large buds of these species escaped damage except where crown consumption occurred.

Byram (1948) theorized that bud damage in the southern pines would be related to bud diameter and the degree of protection provided by the needles and ranked longleaf pine as the most resistant, slash pine as intermediate, and loblolly pine as the most susceptible of the three to bud damage. He also pointed out the importance of considering ambient temperature during a fire, since vegetation at 30 or 40°C is much easier to heat to lethal temperatures than vegetation at 0°C.

Response of red pine (P. resinosa Ait.) to crown scorch has also been studied (Van Wagner 1970, 1973). Sucoff and Allison (1968) reported that an intense spring wildfire in a 47-year-old red pine stand resulted in mortality rates up to 40% for trees which were more than 95% scorched, but fewer than 8% of trees less than 75% scorched died. Kuhlman (1965) artificially defoliated 5-year-old red pines and Scots pines (*P. sylvestris* L.), removing 0, 1, or 2 years of needle growth in midsummer. He measured subsequent shoot elongation and found that removal of needles from the two most recent growing seasons had the strongest negative effect on shoot elongation and that any needle removal reduced shoot elongation in the following season. In his conclusions he stressed the importance of needles for storage of carbohydrates as well as for photosynthesis and theorized that the degree of growth loss was related to the age of the needles removed.

Stem injury. Fire injury to pine stems has been studied by a few investigators who have used both natural fires and artificial heat sources. Most have concluded that duration of the heat source is at least as important as its temperature, because the insulating properties of bark allow the tree to avoid damage to living cambial tissue from short-duration heat pulses. Hare (1965a) used a propane torch to determine insulating value of the bark of 14 species of southern pines and hardwoods. He concluded that bark thickness as well as insulative quality of the bark per unit of thickness were important in explaining fire resistance of the stems of these species. In another study, Hare (1965b) ignited oil-soaked wicks wrapped around trees in an attempt to more closely approximate natural fire conditions and measured cambial temperatures. Lethal temperatures were reached in 2 to 6 min, depending on species. Neither of the two pine species tested (longleaf and slash) reached lethal cambium temperatures before the wick burned out. Where wind affected the flames, leeward temperatures were generally higher than windward temperatures, both outside the bark and at the cambium.

Kayll (1963) used a propane burner and chromel-alumel thermocouples to measure the time for lethal cambial temperatures (taken to be 60°C in this study) to be reached in stems of eastern white pine. Time to reach 60°C was closely related to bark thickness and varied from 2 to 48 min, depending on external temperature applied.

In some cases loblolly pine may be basally scarred or girdled, especially when heavy fuel accumulations are concentrated near the bases of the stems. Ferguson et al. (1960) observed significant mortality of mature loblolly and shortleaf pines resulting from basal wounds inflicted by smoldering debris from a low-intensity fire. Chapman (1942) stated that the response of mature loblolly pines to fire is a function of bark thickness and composition, as well as the temperature and duration of lethal temperatures.

Much of the literature having to do with hardwood stem injury by fire consists of studies in which small stems are selectively removed from under pine stands by prescribed fire. Little and Moore (1945) removed oaks less than 3 cm from under pitch pine (P. rigida Mill.) and shortleaf pine in New Jersey with three annual fires, achieving up to 35% mortality, while inflicting negligible damage to pines greater than 8 cm dbh. Working in the Big Thicket of East Texas, Harrington and Stephenson (1955) reduced the numbers of hardwood stems smaller than 8 cm dbh by more than 80% by applying three spring fires in 5 years to loblolly-shortleaf pine stands. Likewise, Ferguson (1957, 1961) found fire to be effective at removing hardwood stems from pine stands and that summer headfires were more effective than winter backfires. Only 10-20% of the hardwood trees in his study failed to resprout, however, after a single summer fire. He reported a negative correlation between stem diameter and mortality for small sweetgum, post oak (*Quercus stellata* Wangenh.), southern red oak (*Q. falcata* Michx.), and loblolly and shortleaf pines.

Many researchers have found fire susceptibility differences useful for management purposes. Silker (1961) recommended prescribed burning to remove hardwoods from pine stands and set 8 cm dgl as the upper limit for hardwood control, while recommending a minimum stand age of 10 years to avoid pine damage. He stressed the importance of wind for minimizing crown scorch and noted that a series of fires can successively scar and finally kill hardwoods up to 13 cm dgl. Fire also selectively girdles hardwoods under loblolly pine stands (Brender and Cooper 1968, Lotti et al. 1960), although intense headfires can kill small pines (Ferguson 1957). Other authors have set lower diameter and height limits for burning southern pines, and most now agree that single winter fires are ineffective on hardwoods much over 8 cm dgl and risky under pines less than 8 cm dgl and 3-4 m tall, except in the case of longleaf pine (Crow and Shilling 1983).

Summer burning for hardwood control has been studied extensively, and most researchers have concluded that summer fires, where pines are old enough to avoid damage, are much more effective at top-killing hardwoods (Reibold 1955, Hodgkins 1958, Ferguson 1961) and quite effective at killing the rootstocks as well, especially when applied as a series of three or four annual fires (Chaiken 1952, Lotti 1956, Lotti et al. 1960).

Early researchers recognized that some species of hardwoods were more resistant to basal fire scarring than others and that this difference probably had to do with bark characteristics (Kaufert 1933). The relationship between tree diameter and fire resistance was early recognized as well (McCarthy 1933, McCarthy and Sims 1935). However, it was not until the 1960's that researchers took a detailed look at fire injury to hardwood stems. Hare (1965a, 1965b) applied heat to the bark of several southern hardwoods and measured the time elapsed before the cambium reached a lethal temperature of 60°C. Vines (1968) studied the fire resistance of Eucalyptus marginata by applying both natural fires and artificial heat sources to stems of trees and measuring temperature changes outside and under the bark with steel-sheathed chromel-alumel thermocouples. He concluded that bark thickness was the major determinant of resistance to heat and also noted that 60°C appeared to be a reasonable figure for lethal cell temperature. Gill and Ashton (1968), working with Eucalyptus as well, noted that, although bark thickness was important in determining fire resistance, in certain cases this effect can be nullified. They cited E. obliqua which has thick, fibrous bark but is quite susceptible to basal fire injury because the bark is flammable. By contrast E. cypellocarpa trees of the same diameter are more resistant to fire damage, though their bark is thin and smooth, because it is not flammable. They also observed that fire "tolerance" should be viewed from the perspective not only of bark thickness but also of fuel type and amount, which are affected by the trees themselves. Williamson and Black (1981) discussed the evolutionary implications of this idea, using the pine-oak communities of the Florida sandhills as an example.

Response to girdling. Response of trees to girdling has received attention from numerous researchers. Noel (1970) published a comprehensive review of the subject and defined girdling as " . . . the removal of a complete cylinder, either narrow or wide, of all tissues external to the secondary xylem." He noted that in the absence of girdle closure (healing) such treatment is always eventually fatal to the tree parts distal to the girdle, though death may be delayed several years in some cases. Stone (1974) reported that red pine survived complete girdling as long as 18 years because natural root grafts with nongirdled trees sustained the root systems of the girdled trees. Holmes (1984) likewise noted that maple trees (*Acer* spp.) girdled by metal "artificial girdling roots" can survive several years and may in some cases overgrow the girdling apparatus and engulf it. Ueckert (1975) measured regrowth from girdled, felled, burned, 2,4,5-T-sprayed, and basally oiled mesquite (*Prosopis glandulosa* Torr. var. *glandulosa*) and found that basal regrowth from the girdled stems had significantly lower mass per tree than that from felled stems but greater than from the other treatments, including fire. Noel (1970) also commented on the propensity of girdled trees to sprout and stated that "In general, trees of small diameter sprout so profusely as to vitiate the advantages of girdling." Recognizing this limitation of girdling, Crow and Shilling (1983) recommended that periodic winter prescribed burns be used under stands of southern pines to top-kill hardwood sprouts before they reach 8 cm dgl.

Summary

Most researchers who have evaluated fire effects on trees have relied upon natural prescribed fires, or in many cases on wildfires, for their treatments. Often, little or no information about fire intensity, rate of spread, or fuel consumption has been available; thus correlating fire effects with fire parameters was often impossible. The various methods which have been devised to apply controlled heat to trees have often not provided realistic temperature profiles. Conspicuously lacking, therefore, are studies which report fire effects on individual stems in terms of quantities of heat applied or temperature profiles measured in realistic controlled fire environments. The present study was designed to provide quantitative information about the effects of flames on tree boles during prescribed fires.

MATERIALS AND METHODS

Study Area

The experiment was conducted on the Idlewild Research Station, 5 km south of Clinton, Louisiana, in East Feliciana Parish. The area was covered by a loblolly pine stand established in 1979, part of which was artificially regenerated after clearcutting and parts of which were regenerated by the seed-tree and shelterwood methods (Langston 1981). Numerous sprouts of various oak species, sweetgum, and other hardwoods were present. The experimental trees were selected within an area of about 40 ha.

Topography over most of the area is slightly rolling. Soils are predominantly Providence silt loam (Typic Fragiudalf), 0-8% slope, and Lexington silt loam (Typic Paleudult), 1-20% slope (USDA Soil Conservation Service. 1970. Soil survey of Idlewild Experiment Station, Clinton, Louisiana). Loblolly pine site indices (base age 50 yr) range around 31 m (Langston 1981).

Experimental Material

Two hundred trees of three species, loblolly pine, water oak, and sweetgum, 50 in each of four dgl classes, were selected during early fall 1984, permanently marked with numbered metal tags, and flagged with colored tape. Diameter classes were 3 cm (2.5-3.5 cm), 5 cm (4.5-5.5 cm), 7 cm (6.5-7.5 cm), and 9 cm (8.5-9.5 cm). Trees which were scarred, suppressed, unhealthy, or otherwise damaged were not selected for this study.

Because of late fall rains and favorable temperatures, the pines grew approximately 0.5 cm in diameter after they were marked. Therefore the limits of the diameter classes for the pines were changed to 3.0-4.0 cm, 5.0-6.0 cm, 7.0-8.0 cm, and 9.0-10.0 cm, since there was not time to select new trees.

Brush and other trees were removed by hand from within a 2-3 m radius of each experimental tree, including control trees, to facilitate operation of the fire simulator. All clearing was completed before any burns were conducted.

The Fire Simulator

A surface fire simulator (Plates 1-2) was designed to provide a method of applying controlled flames to individual stems (Greene et al. 1986). It simulated either a headfire or a backfire with a moving flame front and controlled wind speed, giving a realistic temperature profile around the base of a small tree (< 15 cm dgl). It did not simulate the crown heating encountered in a real fire because the flame front was too small (56 cm wide) and did not produce enough radiant and convective heat to the edges of the crown. A detailed description of the fire simulator is provided in Appendix A.

Experimental Design

The study included 600 trees in 10 replications and was arranged as three, 4 x 5 factorial experiments in a randomized block design. Trees of three species, loblolly pine, water oak, and sweetgum, and four diameter classes were treated at five levels of intensity including a

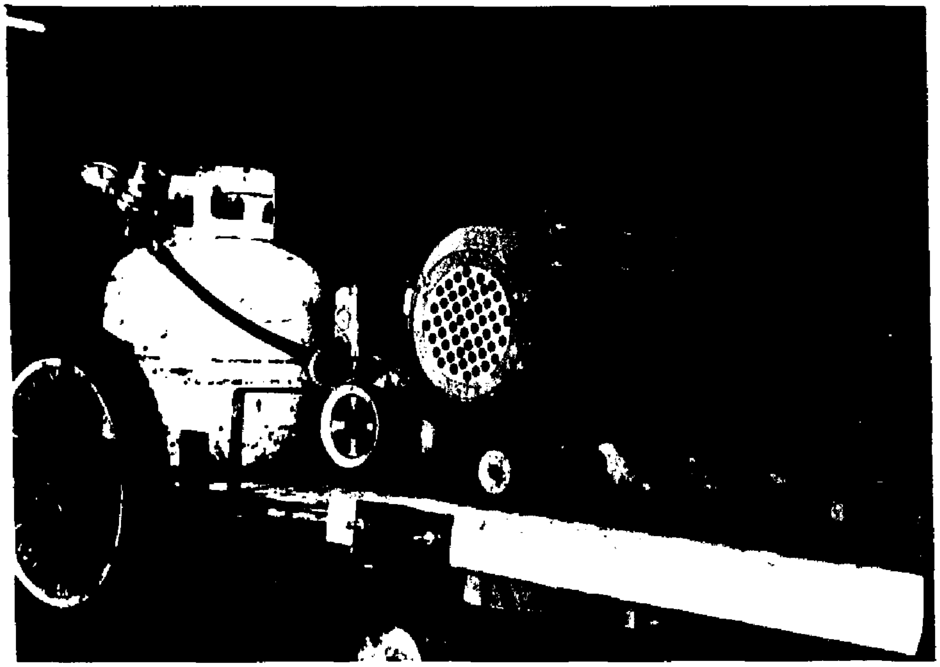

Plate 1. The propane-fueled surface fire simulator.

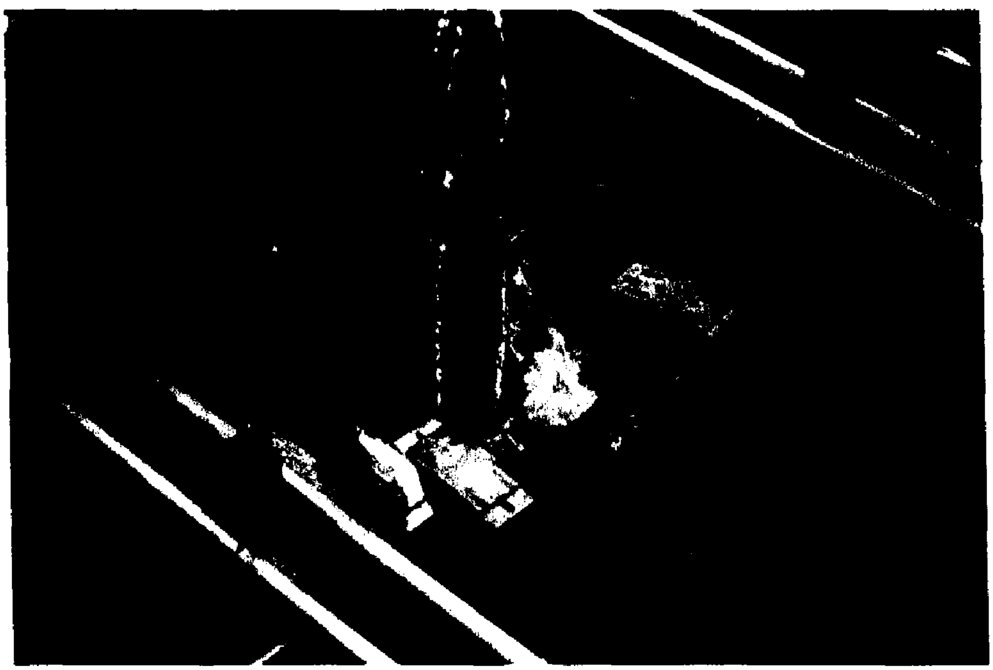

Plate 2. Treatment application.

control or no-burn. Thus, each block or replication consisted of 60 trees, 20 of each species, which were divided equally among the four diameter classes into groups of five trees of the same species and size. Five levels of intensity were randomly assigned within these groups. Treatments were applied in order of replications so that the block effect in the model would be completely confounded with any effect of date-of-burn.

The order of treatments within a replication was determined by tree location; all trees in a given replication in a certain area were treated before trees of that same replication elsewhere were treated. We completed all treatments in a given replication before beginning the next replication. An attempt was made to assign replications to be geographically compact, but it was only partially successful because trees of all species and sizes were not available at every location.

Preburn Measurements

Dgl, dbh, and bark thickness at ground line were measured and recorded for each tree during December 1984. Ground line was defined as 3 cm above the highest mineral soil touching the tree. Diameters were measured to the nearest mm with calipers and recorded as the arithmetic means of the largest diameter and the diameter perpendicular to it. Bark thickness was measured at ground line on the north side of the stem with a standard bark gauge and recorded to the nearest mm. Tree height was measured to the nearest 0.1 ft (3 cm) with a height pole in March 1985, before height growth began.

Immediately before each treatment application, a 1-2 cm^2 sample of bark (all tissues outside the vascular cambium) was collected from the north side of the tree approximately 0.5 m from the ground and immediately sealed in an airtight vial. Samples were not taken at ground line to avoid scarring the bases of the trees and possibly complicating the effect of the fire on the stem. Samples were stored frozen and then analyzed gravimetrically for moisture content. They were weighed wet, dried at 80°C to a constant weight (approximately 48 h); then the moisture content was calculated by difference and reported on a dry-weight basis.

Experimental Procedure

All burns were conducted between February 4 and April 16, 1985. Immediately before each burn, the following parameters were measured and recorded:

--Ambient air temperature, by thermocouple,

--Temperature of bark surface, on both the north and south side of the tree, at 3 cm above ground line, by thermocouple, and

--percent cloud cover, by visual estimation.

Relative humidity was recorded at 1-2 hour intervals throughout the day, and values were assigned to each burn by linear interpolation.

Before each burn we placed four type K (chromel-alumel) thermocouples around the base of the tree. Custom-made thermocouple junctions were enclosed in stainless steel pads 6 x 6 x 2.5 mm and placed 3 cm above the mineral soil and 5 mm from the bark on the leeward, windward, right flank, and left flank sides of the tree, which corresponded, respectively, to north, south, east, and west sides for most trees since we burned from north to south into a south "wind" whenever possible. Thermocouple wires extended up the tree and were attached 30-40 cm above the ground with steel wire. Below the attachment point the wires were not allowed to contact the tree.

Thermocouple wires were insulated with fiber glass fabric, but it became necessary to cover the part of the wire which was repeatedly exposed to flame with aluminum foil to prevent the disintegration of the fiber glass. In addition we covered the rest of the wire with plastic tape to prevent damage to the insulation from abrasion.

Thermocouples were attached to a Campbell Scientific CR21A micrologger which we programmed to store the temperatures of all four thermocouples at intervals of 2 s. After each burn, data were transferred to a cassette tape.

Flame-resistant mats were placed on either side of the tree under the path of the burners to avoid starting wildfires. Natural fuel was removed from around the treated trees in order to maintain better control over heat application. When the fire simulator was in place and the preburn measurements taken, we started the gasoline-powered generator, lit the gas elements, activated the CR21A, started the flame front moving, and turned on the fan. After the flame was past the tree and the temperature recorded by all four thermocouples had dropped below 60°C, we turned off the flame and the fan and removed the fire simulating apparatus and thermocouples. The cutoff level of 60°C was chosen because it is an average lethal temperature cited in the literature (Kayll 1963, Hare 1965a, 1965b, Vines 1968), though actual lethal temperature depends on exposure time (Nelson 1952).

Fire Intensity Determination

Propane pressure settings used in treatment applications were 0.141, 0.422, 0.703, and 0.984 kg/cm^2, which produced propane flow rates of 0.473, 0.851, 1.059, and 1.301 g/s. Greene et al. (1986) calculated fireline intensity (Byram 1959) values from these flow rates of 36, 64, 80, and 98 kJ/s/m. For the purposes of this study, these fireline intensity values will herein be referred to as "fire intensity," while the area under a temperature x time curve (described below) will be called "temperature exposure."

Crown Scorch Measurement

Crown discoloration resulting from heat damage of needles (crown scorch) occurred on several of the treated loblolly pines (Plate 3). We therefore estimated the percent of the crown affected by scorch for all pines treated in the study. Estimates were made 1-2 weeks after treatment.

Soil Moisture

Composite soil samples were taken weekly during the treatment period from the upper 15 cm of soil on the treatment area. The 50-100 g samples were collected from the area in which treatments were being applied at the time. Moisture content was determined gravimetrically by weighing the samples, drying them at 100°C for 72 h, and reweighing.

End-of-season Measurements

In December 1985 tree height, dbh, and dgl were remeasured to determine growth rate in the first post-burn growing season. Heights of

Plate 3. A 7-cm loblolly pine immediately after treatment with the propane-fueled surface fire simulator.

trees which died and subsequently lost parts of their crowns due to breakage were measured as they stood. Trees which had died and fallen over (broken at the base) were held upright on their stumps for height determination.

Mortality and scarring of trees were measured by classifying each tree into one of the following categories: live, unscarred; live, scarred; live, girdled; and dead. Presence or absence of live basal sprouts was also noted. A stem was considered dead if no live cambium could be located distal to the fire injury. Scars were recognized by the presence of sunken areas, sloughing bark, oozing gum (especially on loblolly pine and sweetgum), and exposed wood. When necessary, scars were probed with a knife blade to determine their extent. The presence of a scar was not recorded solely on the basis of oozing gum, since gum exudation can be a symptom of other forms of injury such as insect attack. A tree was considered girdled if it was scarred in a continuous band of any width all the way around the stem, so that no phloem connection existed across the fire injury.

Since a large percentage of the hardwoods fell into the "live, girdled" category, we decided to postpone final evaluation of mortality and damage until full leaf expansion was complete the following spring (May 1986) to see if the remaining girdled trees would fail to leaf out and thus die.

In May 1986 I re-evaluated the responses of the trees to burning. Mortality was tallied again, and the presence, location and extent of scarring was recorded. Each stem was visually divided into four 90° quadrants corresponding to the cardinal directions. Scars which covered less than 90° of the circumference of the tree (including the area covered by newly formed callus tissue) were assigned to the quadrant in which they occurred; if scars overlapped two quadrants, they were assigned to the one they occupied more of. Scars which covered between 90° and 180° of circumference were assigned to two quadrants in a similar manner. Scars which occupied more than 180° but less than 360° were assigned to three quadrants; only completely girdled trees were recorded as having been scarred on all four quadrants. Although the third category in this classification scheme is twice as large as the first two in theory, in practice very few trees had between 270° and 360° of their circumference scarred, and the narrowest bridge of surviving cambium on any tree was approximately 2 cm wide. Presence or absence of live sprouts was recorded at this time also.

Calculations

Three variables were calculated from each temperature x time curve: the maximum temperature recorded by the thermocouple, the duration of temperatures in excess of $60^{\circ}C$, and the approximate area under the temperature x time curve above $60^{\circ}C$, or temperature exposure, in $^{\circ}C{*}s$, given by

$$E = \mathrm{SUM}_{i=1}^{n} [I(t_i - 60)] \quad , \; t>60 \qquad \text{(eq. 1)}$$

where: E = temperature exposure, $^{\circ}C{*}s$,

I = temperature measurement interval, s,

t_i = measured temperature, $^{\circ}C$, taken at time i,

n = number of intervals during which $t>60^{\circ}C$.

Height growth to the nearest 3 cm and diameter growth at ground line and at breast height to the nearest mm were calculated for the 1985 growing season. In addition, the degree of scarring was estimated by counting the number of quadrants scarred, as described above. Thus, the variable (degree of scarring) could take integer values from 0-4, ranging from no damage to girdled.

Statistical Treatment

Growth models. Diameter and height growth data for each species were subjected to analysis of variance and analysis of covariance in order to isolate important predictor variables. Independent variables tested included initial dbh, initial height, Byram fire intensity, mean temperature exposure, and degree of scarring. Only dbh or tree height (all species) and degree of scarring (pine only) significantly affected diameter growth in the first year after burning. Statistical models used in the analysis are presented in Table 1.

Girdling probability models. The logistic regression procedure provides a means of deriving models which predict the probability of a particular outcome in a probability distribution given a set of x variables which are related to the outcome (Harrell and Lee 1985). In the binomial case, the value

$$\ln [P/(1-P)]$$

where P = probability of one of the two outcomes is called the logit of the probability and is modeled as a function of a number of x variables.

Table 1. Statistical models used in analysis of dbh growth of 397 nongirdled loblolly pine, water oak, and sweetgum trees.

Species	Source	D. F.	E. M. S.[a]
Loblolly pine	Dbh	1	$e + q_1(dbh)$
	Scar degree	2	$e + q_2(DS)$
	Error	186	e
	Total	189	
Water oak	Dbh	1	$e + q_3(dbh)$
	Error	100	e
	Total	101	
Sweetgum	Dbh	1	$e + q_4(dbh)$
	Error	103	e
	Total	104	

[a] e = error variance; $q_n(dbh)$ = fixed dbh effect; $q_2(DS)$ = fixed scar degree effect.

The fundamental assumption of the binary logistic model (Zarnoch et al. 1984, SAS Institute, Inc. 1983) is that

$$P = [1 + \exp(-(B_o + B_1X_1 + \ldots + B_kX_k))]^{-1} \qquad \text{(eq. 2)}$$

where P = the probability of the chosen outcome,

B_k = model coefficients, and

X_k = independent variables.

Logistic regression has several advantages over other probability modeling procedures such as discriminant analysis. It is more robust against non-normality and heterogeneity of variance of the predictor variables, continuous and nominal independent variables can be included to predict binary, ordinal, or nominal dependent variables, and the independent variables need not be grouped into classes to obtain probabilities (Harrell and Lee 1985).

In the present study I attempted to develop models which described the probability of a stem's being girdled as precisely as possible, while also trying to minimize the number of X variables included in the models. I tested all of the following variables as possible predictors of the girdling probability, both in stepwise procedures and as components of smaller logistic models:

1. Dgl
2. Dbh
3. Tree height
4. Bark thickness
5. Maximum temperature on each side of the tree

6. Mean maximum temperature
7. Duration of lethal temperatures on each side
8. Mean duration
9. Temperature exposure on each side
10. Mean temperature exposure
11. Bark moisture content
12. Relative humidity
13. Ambient temperature
14. Leeward and windward preburn bark temperatures

Variables which proved significant in first order tests were also tested for second and third order significance; important interactions were tested also.

In order to avoid multicollinearity in the models, the variables were grouped into four categories containing highly correlated variables but with low correlations between categories. Variables were grouped as either tree size descriptors, fire intensity descriptors, moisture descriptors, or preburn temperature descriptors. A maximum of one variable was chosen from each group in any given prospective model.

In general, I assumed that tree size descriptors (dbh, dgl, height, bark thickness) would negatively influence the probability of girdling, while preburn temperature and fire intensity descriptors would positively influence the probability. No *a priori* assumptions were made concerning the effects of moisture descriptors on the probability of girdling.

Other statistical treatments. The following data were subjected to analysis of variance, and means, where of interest, were separated by

Duncan's multiple range test (Steel and Torrie 1980):

1. Bark moisture content
2. Bark surface temperature
3. Maximum fire temperature
4. Duration of lethal temperatures
5. Temperature exposure
6. Degree of scarring
7. Percent girdled
8. Percent crown scorch

The relationship between tree diameter and sprout production was examined by regression analysis.

RESULTS AND DISCUSSION

Environmental Parameters

Precipitation. Precipitation during 1985 at the Idlewild Research Station was relatively evenly distributed with the exception that more than 390 mm of rain fell in October, while less than 15 mm fell in November. Total precipitation for the year was 1582 mm, an average of 132 mm per month (Figure 1, Thompson et al. 1986).

Temperature. Except for extremely cold temperatures recorded Jan. 22 and 23, most temperature readings were near normal during 1985 at the Idlewild Research Station. The temperature fell below $0^{o}C$ on 49 days during January, February, and December and exceeded $32^{o}C$ on 70 days during June-September. The lowest temperature recorded for the year was $-14.4^{o}C$, while the highest was $35.6^{o}C$ (Thompson et al. 1986).

Soil moisture content. Soil moisture content (dry weight basis) measured in the upper 15 cm of soil on the study area did not fall below 23% and was as much as 48% during the treatment period (February-April 1985) (Table 2).

Burning conditions. Conditions under which the trees were treated are presented in Table 3. Air temperatures varied from $1^{o}C$ to $33^{o}C$, with a mean of $21^{o}C$ across all burns. No burns were conducted when ambient temperature was below $0^{o}C$ in order to avoid the complicating effect of intercellular ice, whose heat of fusion might confer extra heat resistance on stem tissues (Byram 1948).

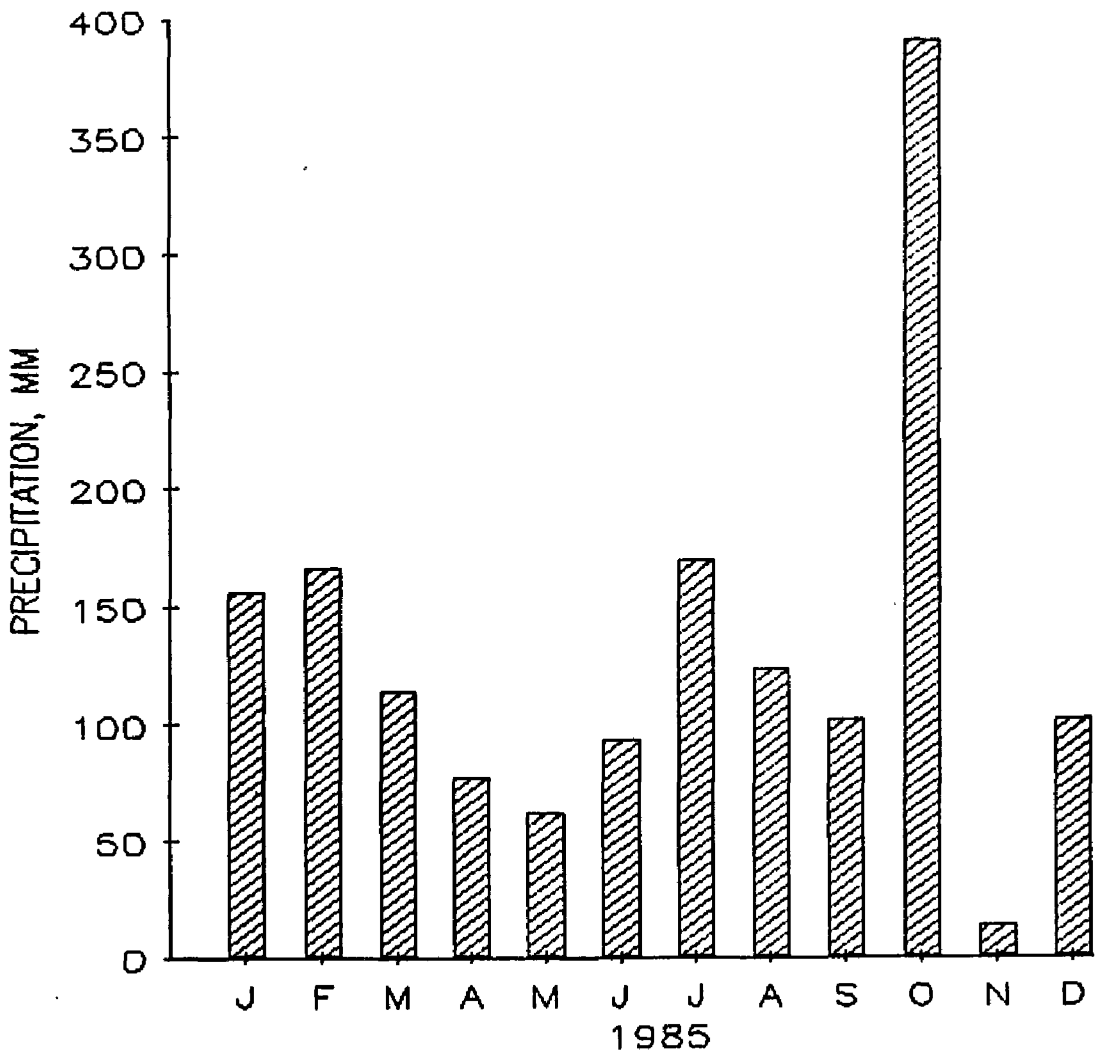

Figure 1. Monthly precipitation in 1985, near the study site at Idlewild Research Station, Clinton, LA. Data from Thompson et al. 1986.

Table 2. Soil moisture content, percent dry-weight basis, in the upper 15 cm of soil from selected locations at Idlewild Research Station, Clinton, LA, February-April 1985.

Sample number	Date	Percent moisture
1	Feb. 8	36
2	Feb. 16	36
3	Mar. 1	38
4	Mar. 7	23
5	Mar. 14	36
6	Mar. 21	27
7	Mar. 25	34
8	Apr. 2	30
9	Apr. 11	48

Table 3. Mean environmental parameters at time of burning, by species and diameter class, for 480 burns conducted with the propane-fueled fire simulator.

Species	Parameter[a]	3 Mean	3 S.E.	5 Mean	5 S.E.	7 Mean	7 S.E.	9 Mean	9 S.E.
		Ground-line diameter class (cm)							
Lob. pine	Air temp., °C	21	0.8	20	0.9	21	1.1	21	0.8
	Bark surface temp., N, °C	22	0.8	22	0.9	23	1.0	22	0.8
	Bark surface temp., S, °C	21	1.0	20	1.0	21	1.2	21	1.0
	Relative humidity, %	56	3.6	60	3.5	56	3.2	55	3.0
	Cloud cover, %	50	6.7	48	7.4	36	6.2	40	6.0
	Bark mois. cont.[b,c], %	28a	2.5	25ab	1.1	24ab	1.1	22b	0.9
Water oak	Air temp., °C	23	0.8	21	0.8	22	0.7	21	0.9
	Bark surface temp., N, °C	24	0.8	21	0.8	23	0.7	23	0.9
	Bark surface temp., S, °C	23	0.9	21	0.9	22	0.9	21	1.1
	Relative humidity, %	53	2.5	62	2.5	57	2.5	53	2.5
	Cloud cover, %	42	5.8	41	7.0	50	6.8	40	6.5
	Bark mois. cont., %	56a	3.0	52ab	3.0	44bc	2.9	41c	2.9
Sweet-gum	Air temp., °C	22	0.9	22	0.8	21	1.1	21	1.0
	Bark surface temp., N, °C	24	1.0	23	0.8	23	1.1	22	1.0
	Bark surface temp., S, °C	22	1.2	22	1.0	21	1.2	22	1.1
	Relative humidity, %	48	3.3	55	3.1	52	2.7	52	2.6
	Cloud cover, %	23	6.0	51	6.7	35	6.6	45	6.2
	Bark mois. cont., %	65a	4.4	53b	4.2	46b	2.9	36c	2.5

[a] Means are across all fire intensities (except 0); $n = 40$.

[b] Bark moisture content means within a species followed by the same letter are not significantly different at the 0.05 level according to Duncan's multiple range test.

[c] Loblolly pine bark moisture content was significantly different from water oak or sweetgum bark moisture content at the 0.05 level according to Duncan's multiple range test.

Range of air temperatures was rather broad, exceeding the usual recommended temperature extremes for prescribed winter backfires aimed at controlling small hardwoods in southern pines (Lotti et al. 1960, Crow and Shilling 1983); however, this was to a great extent unavoidable because of time constraints during the burning season and proved fortuitous as it provided an opportunity to test the effects of burning under a broader set of conditions.

Bark surface temperature was measured on the north (shaded) side of the stem as well as on the south side, to determine if solar heating of the south side might be great enough to contribute to scar formation (Table 3). Mean bark temperature on the south side, however, exceeded mean temperature on the north side by only 1.3^{o}C. Though this difference was statistically significant ($P = 0.0001$), it's effect on scar formation was probably negligible. A possible explanation for the small difference is that many stems were shaded by adjacent vegetation when the burning was applied, and on many days clouds screened the area from direct solar radiation. Cambium temperature was not measured but would perhaps have provided a more definitive measure of susceptibility to heat.

Because of its possible influence on bark moisture content, and thus thermal conductivity of the bark, relative humidity was monitored during the burn applications. Percent relative humidity varied from a low of 13% to a high of 99%, with a mean of 55% over all burns (Table 3). Relative humidity was indeed somewhat correlated with bark moisture content of loblolly pine [Pearson correlation coefficient (PCC) = 0.41, $P = 0.0001$] and of water oak (PCC = 0.37, $P = 0.0001$), but not at all in the case of sweetgum (PCC = 0.009, P = 0.91). This difference probably reflects morphological differences in bark between the species, perhaps the ability of the phelloderm to absorb atmospheric water, or the proportion of dead tissue external to the vascular cambium.

Cloud cover (Table 3) proved only slightly correlated with south side bark temperature (PCC = -0.25, P = 0.0001). Percent cloud cover was, as was expected, correlated with relative humidity (PCC = 0.59, P = .0001).

Bark moisture content (Table 3, Figure 2) was measured before each burn because I thought that it might be related to the thermal conductivity of the bark, and thus have an impact on heat resistance of stems. Loblolly pine bark moisture content was significantly lower than that of either water oak or sweetgum ($P < 0.05$), and dgl negatively influenced bark moisture content. Both the species and the diameter effects on bark moisture content probably reflect the proportion of dead outer bark available to absorb and release atmospheric water in response to fluctuations in humidity and to the presence of dew and rain on the bark surface, as well as changes in bark composition with diameter and between species.

Fire Parameters

Temperature maxima. Maximum temperatures were determined in this study so that they could be tested as predictors of tree responses, and so that the results of this study could be compared with other studies in which temperature maxima were reported. Mean temperature maxima and standard deviations for each intensity are presented in Table 4 and

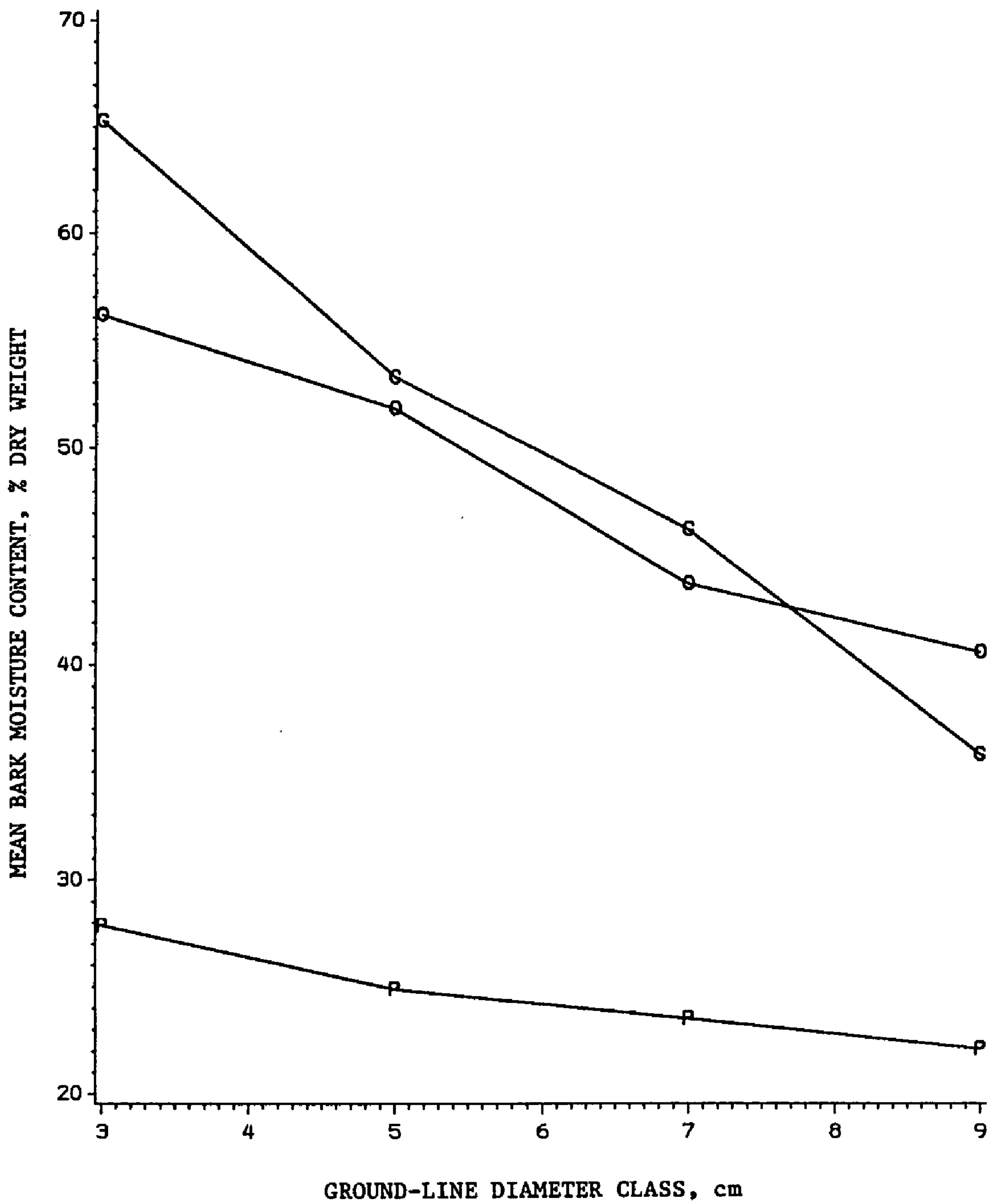

Figure 2. Mean bark moisture content as a function of ground-line diameter class, for 480 trees of three species at the time of treatment with the propane-fueled surface fire simulator. P = loblolly pine; O = water oak; G = sweetgum.

Table 4. Mean temperature maxima, duration of lethal temperatures, and temperature exposures for 480 burns with the propane-fueled fire simulator. (Data from Greene et al. 1986; used by permission of Society of American Foresters.)

Fire intensity	Thermocouple position	Maximum temperature			Duration of lethal temperatures			Temperature exposure		
		Mean[a]	S.D.	C.V.	Mean[a]	S.D.	C.V.	Mean[a]	S.D.	C.V.
kJ/s/m		----°C----		%	seconds		%	---°C*s---		%
36	Leeward	139a	78	56	141a	52	37	4960a	4370	88
	Windward	264a	111	42	194a	33	17	14180a	6600	47
	R. flank	194a	102	53	173a	42	24	9150a	6170	67
	L. flank	204a	109	53	175a	42	24	9940a	6480	65
64	Leeward	302b	136	45	220b	41	19	17840b	8400	47
	Windward	490b	131	27	244b	25	10	33690b	8850	26
	R. flank	414b	144	35	237b	33	14	27210b	9190	34
	L. flank	441b	157	35	239b	32	13	29060b	10090	35
80	Leeward	385c	133	35	249c	40	16	26960c	8880	33
	Windward	632c	98	16	257c	25	10	48410c	8770	18
	R. flank	548c	143	26	257c	28	11	40680c	10370	25
	L. flank	583c	122	21	256c	29	11	43460c	10250	24
98	leeward	489d	135	28	264d	41	16	36570d	12250	33
	windward	718d	89	12	274d	24	9	60460d	9740	16
	R. flank	627d	117	19	274d	28	10	51300d	10520	20
	L. flank	658d	132	20	275d	30	11	53460d	12100	23

[a] Means in the same column from the same thermocouple position followed by the same letter are not significantly different at the 0.05 level according to Duncan's multiple range test. Mean temperature maxima for leeward, windward, right, and left flanks were all significantly different, leeward mean duration differed significantly from durations at the other three positions, and leeward and windward temperature exposures differed form each other and from those measured on the flanks, at the 0.05 level of significance according to Duncan's multiple range test.

Figure 3. These maxima correspond fairly closely with other published reports of temperatures encountered in surface fires in natural fuels (Lindenmuth and Byram 1948, Davis and Martin 1960, Hare 1961, Whittaker 1961, Tunstall et al. 1976, Williamson and Black 1981).

In the present study maximum temperatures recorded 3 cm above the soil surface varied directly with fire intensity and were highest on the windward side of the trees, lowest on the leeward side, and intermediate on the flanks of the stem (Table 4, Figure 3). This pattern differs from that reported for backfires by Hare (1961) in which lee temperatures are the same or higher than windward temperatures. This discrepancy may have been caused by unnatural wind and/or flame patterns produced by the fire simulator, or it might have resulted from the positioning of the thermocouples with respect to the ground. Higher placement might have resulted in a more natural pattern of temperature distribution being recorded. Also, since the trees used in this study were all less than 10 cm dgl, they may not have been large enough to develop the typical "chimney" effect which causes high temperatures on the lee side of larger stems (Gill 1974).

Duration of lethal temperatures. Duration of the heat pulse is as important as its temperature in determining the response of woody stems to fire. For unprotected plant cells the duration of exposure to high temperature determines, within a range of temperatures, the exact temperature at which cell death occurs. For most higher plant cells studied thus far, this range is between 50°C and 64°C (Nelson 1952, Hare 1961). Within this temperature range lethal temperature is inversely related to exposure time, so that long exposures are necessary to kill

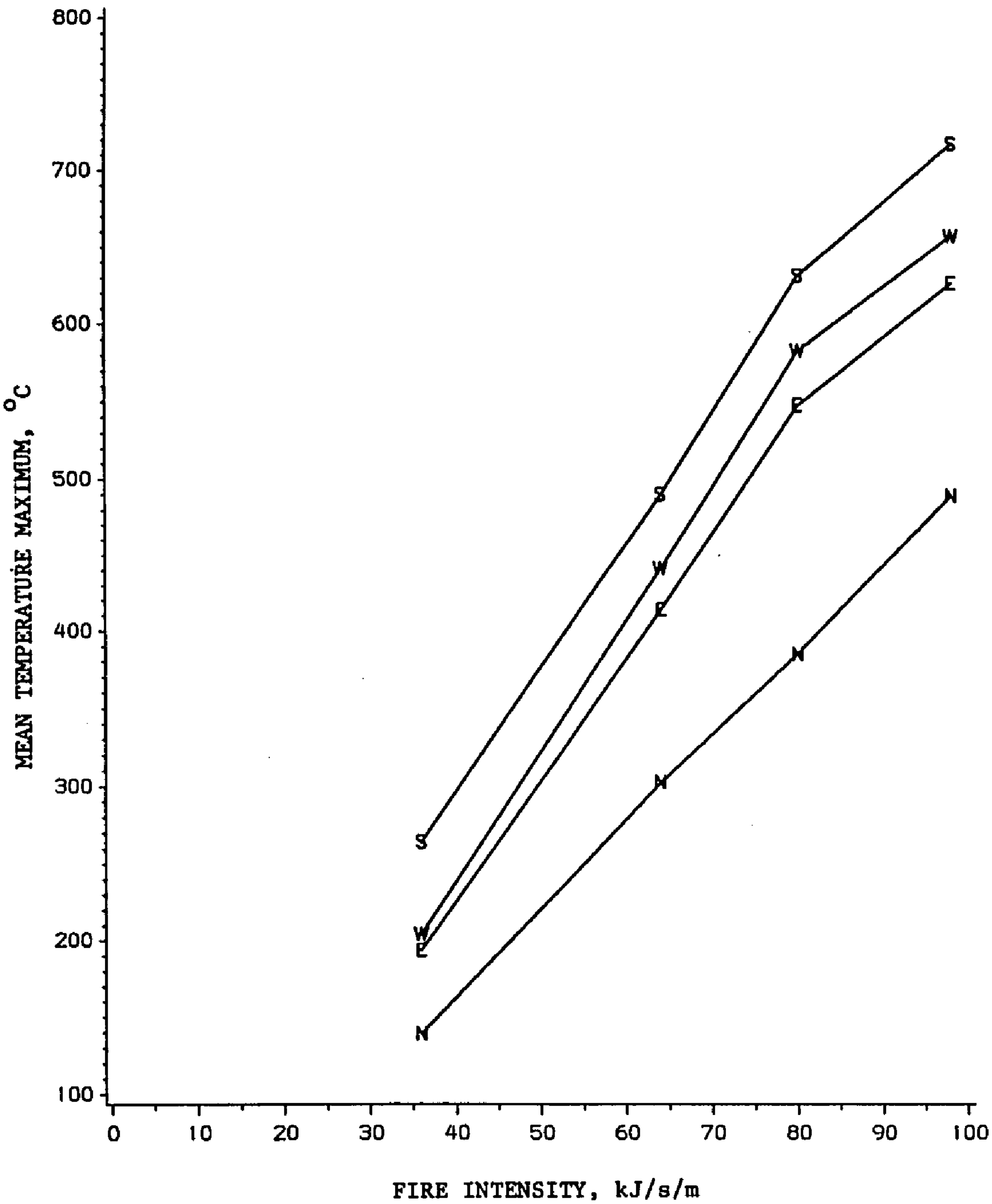

Figure 3. Mean temperature maxima at four positions around the bases of 480 trees as a function of fire intensity during treatment with the propane fueled fire simulator. S = south (windward); N = north (leeward); E = east; W = west.

cells at 50°C, while exposure to 64°C will kill them in 2-3 s.

In the case of cambial cells, which are protected beneath secondary phloem, phellem, and phelloderm tissues, an additional factor enters the lethal temperature-time relationship. The heat pulse must not only be long and hot enough to kill cells, it must also be long enough to cause enough heat to pass through the bark to raise the cambium to lethal temperatures. A further complicating factor is that, once the cambium is raised above lethal temperature, the bark may serve to prevent cooling and prolong high temperatures, possibly increasing the possibility and/or extent of scarring.

Duration of temperatures above 60°C in the present study followed the same general patterns as did temperature maxima, except with less variation within intensity levels. Durations were shortest on the leeward side and slightly longer on the windward side than on the flanks for the lower two levels of intensity (Table 4, Figure 4).

Temperature exposure. Temperature exposure, or the integral of the temperature x time function, combines the information about temperature and duration, giving a single number to describe the amount of heat applied to the surface of a stem. This index provides more information about a heat pulse than temperature or duration alone. Other researchers have used indices combining temperature and time to describe fire impact on vegetation. Rasmussen (1981) found that temperature exposure was better than maximum temperature for predicting top-kill in huisache [*Acacia farnesiana* (L.) Willd.] under artificial burning conditions. Lindenmuth and Byram (1948) used slow-heating thermocouples to measure flame temperatures, thus obtaining an index dependent on

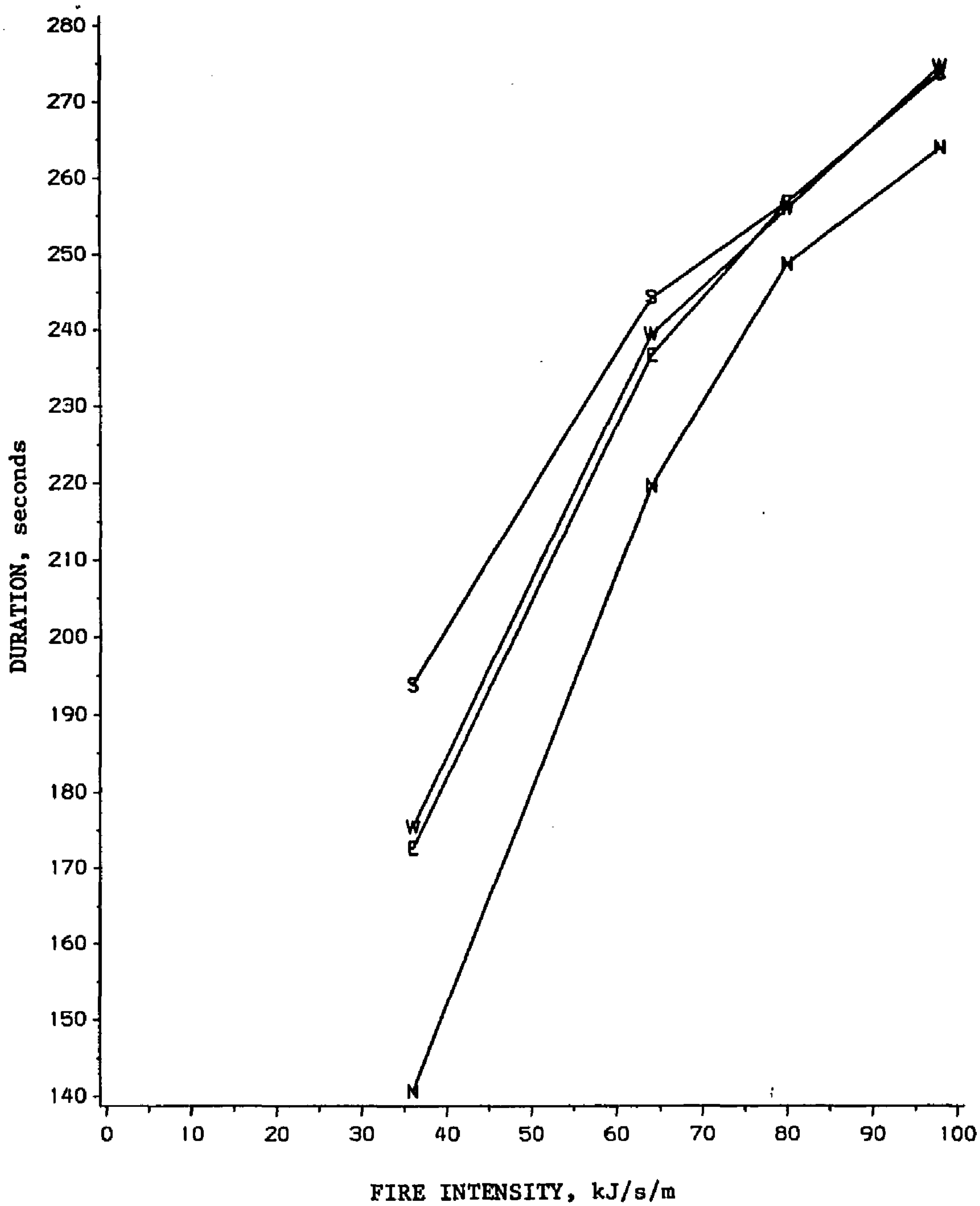

Figure 4. Mean duration of lethal temperatures at four positions around the bases of 480 trees treated with the propane-fueled fire simulator. S = south (windward); N = north (leeward); E = east; W = west.

temperature and duration of exposure which they referred to as the "heat factor."

Temperature exposures in the present study varied directly with propane flow rate (and intensity) and were highest on the windward side of the trees, lowest on the leeward side, and intermediate on the flanks (Table 4, Figure 5). This pattern reflects those of the maxima and durations. Individual temperature exposure values varied between 0 and 85000^{o}C*s.

Magnitudes of temperature exposures measured in this study corresponded with those calculated from published temperature x time curves for surface fires in natural fuels. Davis and Martin (1960) published temperature x time curves at 30 and 122 cm from the ground in a headfire and a backfire. At 30 cm, temperature exposures calculated from their graph were approximately 46000^{o}C*s for the headfire and 25000^{o}C*s for the backfire. Maxima and durations were 870^{o}C, 215+ s, and 288^{o}C, 190 s, respectively. Tunstall et al. (1976) measured temperature x time relationships for 14 grass fires on four sides of asbestos cylinders. Mean windward temperature exposures, calculated from their figure, were approximately 28000^{o}C*s for the lee side and 9700^{o}C*s on the windward side. Simulated fires measured by Hare (1965b) produced temperature exposures near 37000^{o}C*s on the windward side and 74000^{o}C*s on the leeward side of stems 30 cm above a flaming, oil-soaked wick.

The shapes of the temperature x time curves produced by the fire simulator are similar to those reported by other researchers for fires in natural fuels (Hare 1965b, Davis and Martin 1960, Tunstall et al.

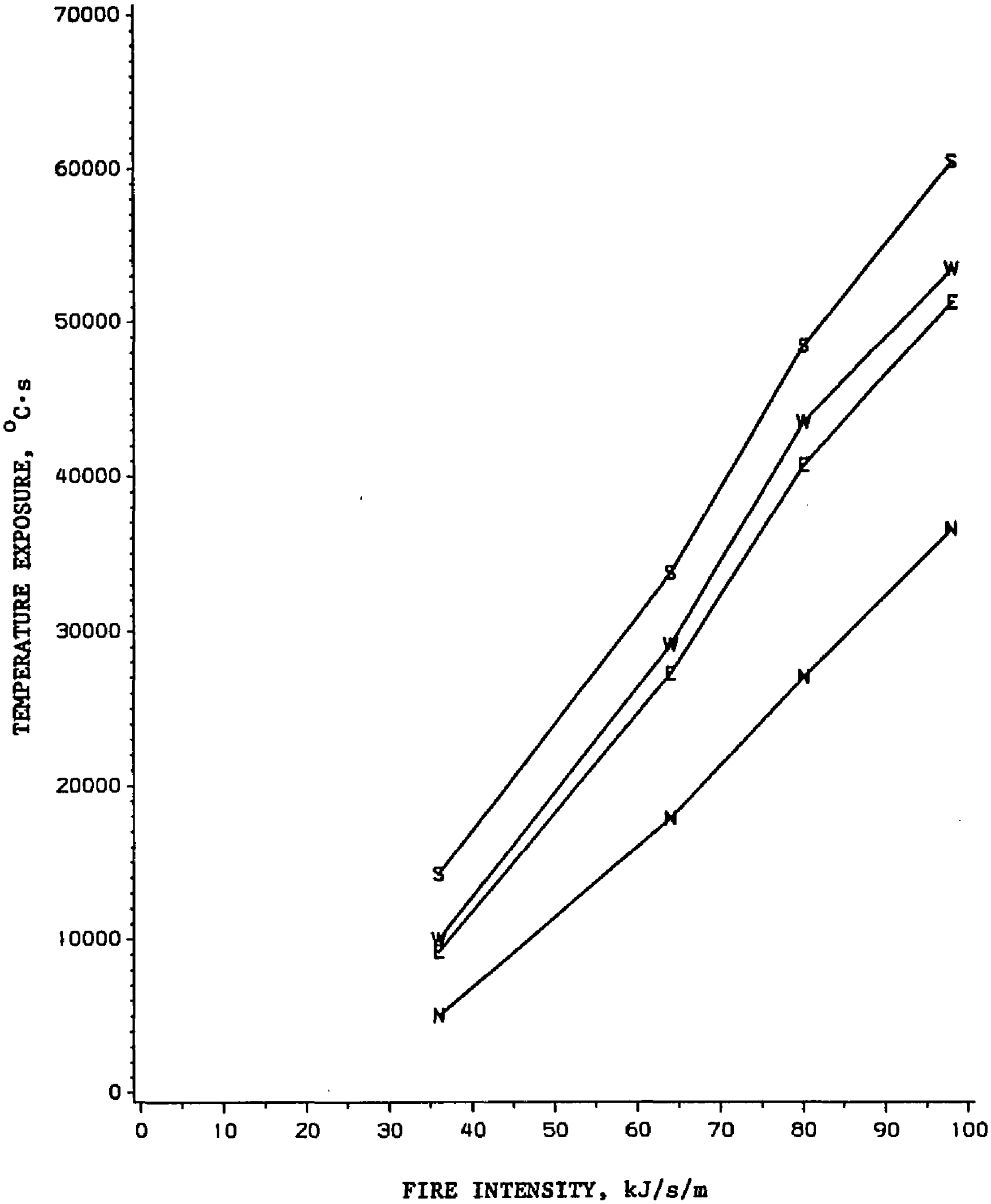

Figure 5. Temperature exposure as a function of fire intensity at four locations around the bases of 480 trees during treatment with the propane-fueled fire simulator. S = south (windward); N = north (leeward); E = east; W = west.

1976). There is an initial, rapid temperature increase as the flames approach the tree, a peak, and a slower, exponential decline. This general pattern holds regardless of thermocouple position or intensity level (Figures 6-9).

Plant Responses

Scarring and girdling. For the purposes of this study a scar was defined as an area of vascular cambium which has been killed, leaving dead bark and/or exposed wood. If a scar extended around a stem in a continuous band, the stem was considered girdled. The degree to which a stem was scarred in this study depended largely on the species and diameter of the stem and the intensity of the fire.

As expected, loblolly pine stems were the least affected by the fires ($P < 0.05$, Duncan's multiple range test, percent-girdled means), with only 35 trees scarred, 10 of which were girdled (Tables 5-7). The resistance of the pine stems to fire is attributable to their thick porous bark, which slows the conduction of heat to the living tissues of the vascular cambium and prevents damage. Water oak and sweetgum stems were more heavily scarred by the fire treatments, with 143 of 200 water oaks scarred by fire (98 girdled), and 142 of 200 sweetgum trees scarred by fire (95 girdled). One sweetgum and two water oaks were scarred by agents other than fire during the study period.

Stems tended to scar first on the windward side of the stem near the base, and least frequently on the leeward side. This pattern reflects the distribution of temperatures around the bases of the stems as measured with the thermocouples and was apparent on most of the scarred trees.

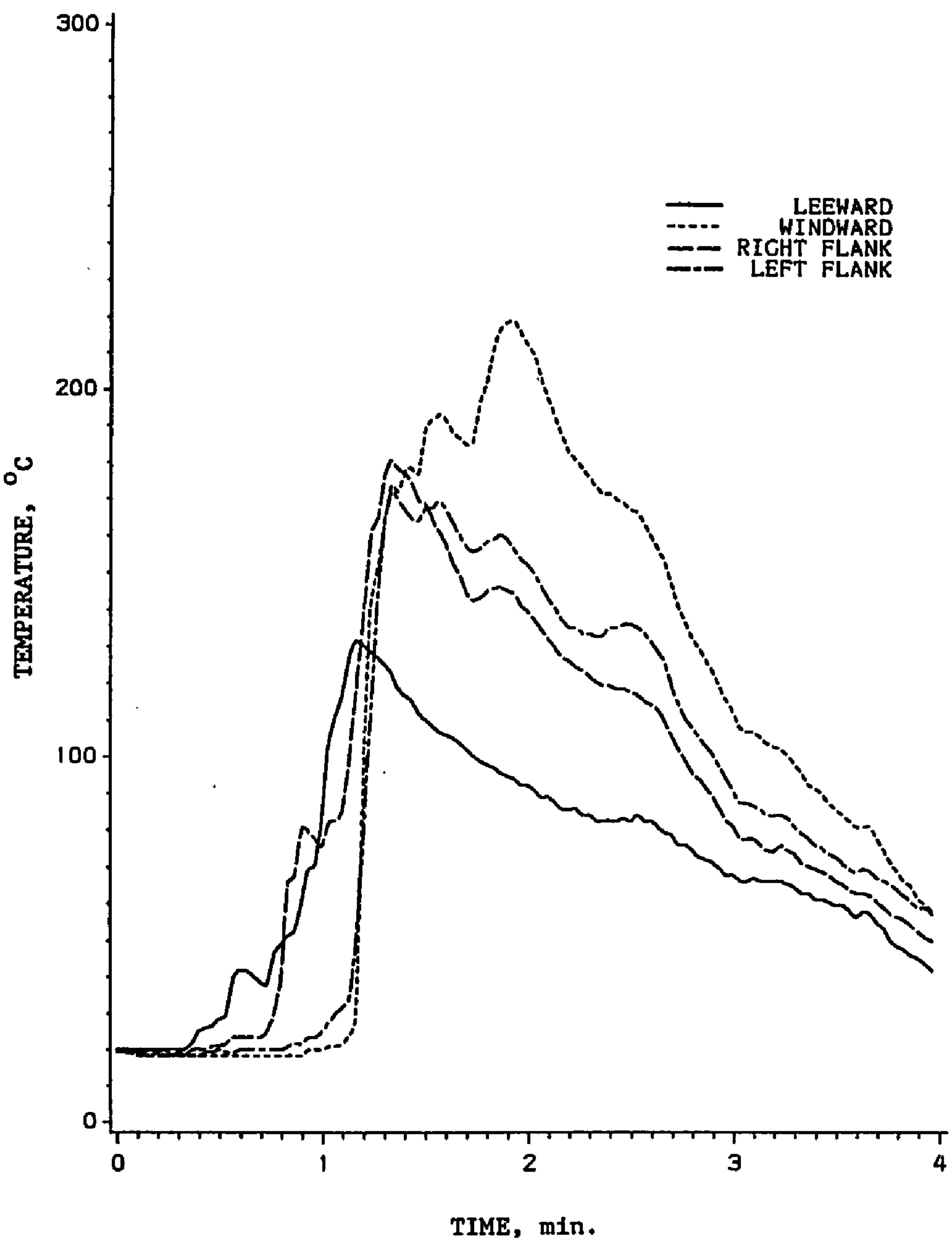

Figure 6. Temperature profile at four locations around the base of a tree during treatment with the propane-fueled fire simulator at 36 kJ/s/m.

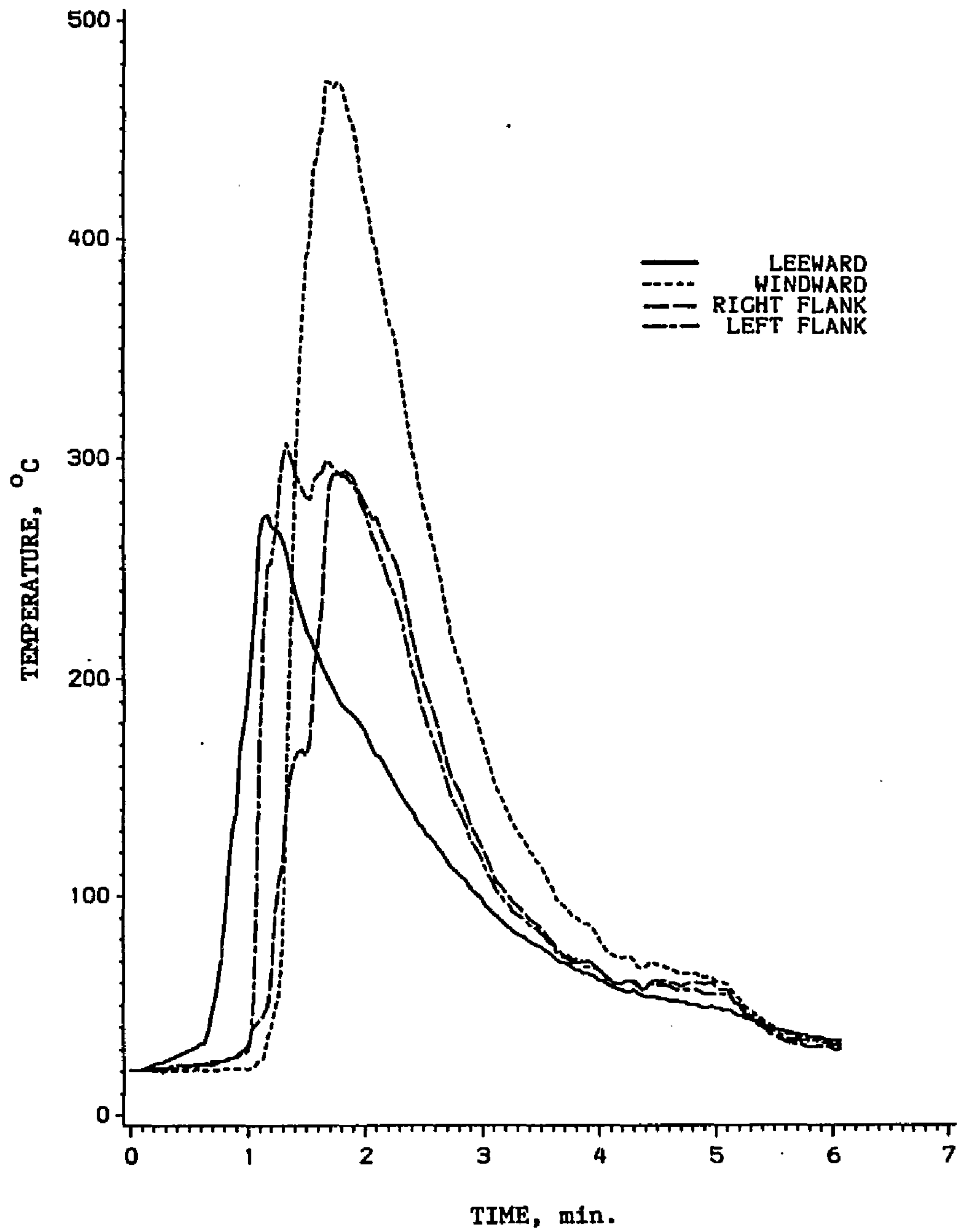

Figure 7. Temperature profile at four locations around the base of a tree during treatment with the propane-fueled fire simulator at 64 kJ/s/m.

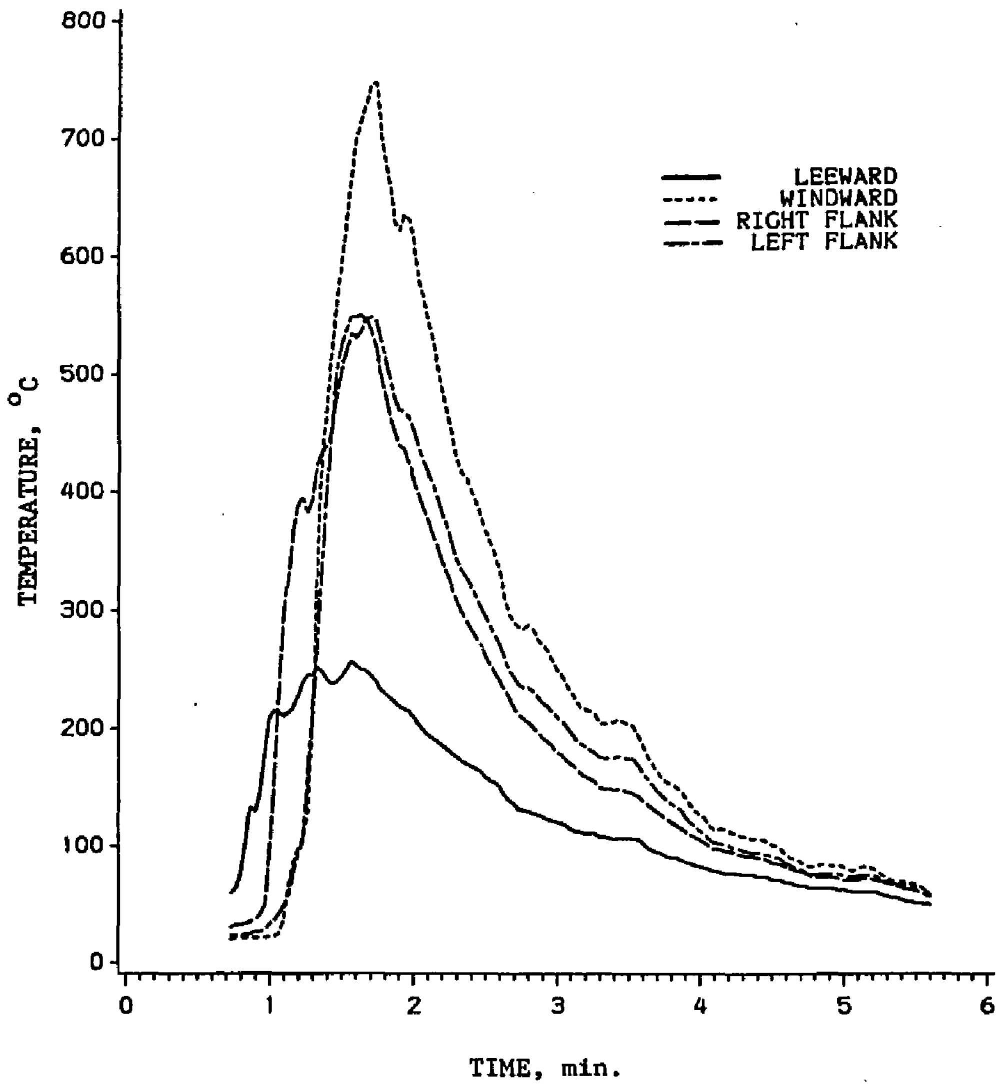

Figure 8. Temperature profile at four locations around the base of a tree during treatment with the propane-fueled fire simulator at 80 kJ/s/m. (Figure originally published by Greene et al. 1986; used by permission of Society of American Foresters.)

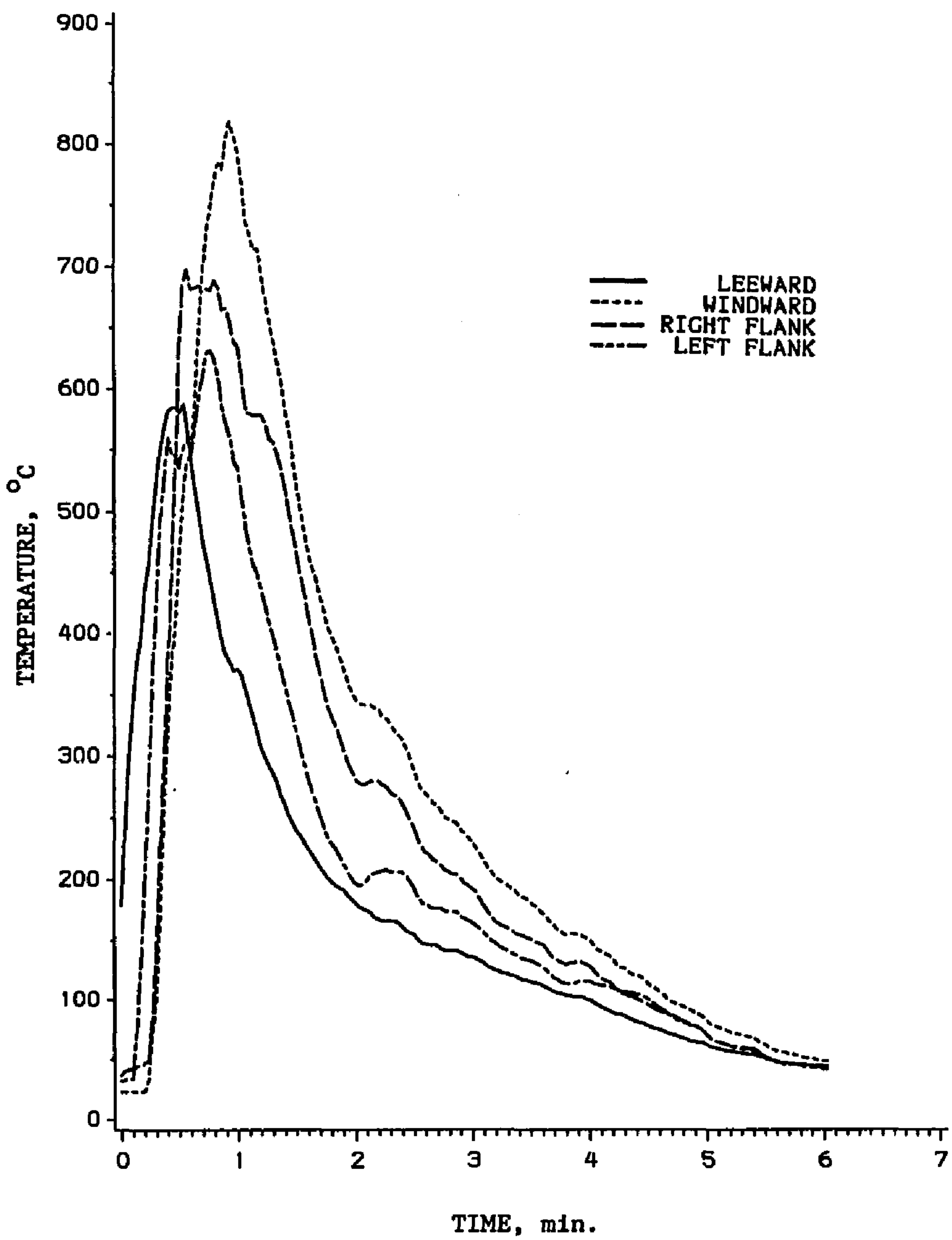

Figure 9. Temperature profile at four locations around the base of a tree during treatment with the propane-fueled fire simulator at 98 kJ/s/m.

Table 5. Mean degree of scarring (average number of quadrants scarred per tree) as of May 1986, for 600 trees of three species in four diameter classes treated with five fire intensities with the propane-fueled fire simulator.

Species[a]	Intensity[b]	-----Ground-line diameter class[c] (cm)----- 3		5		7		9	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
	kJ/s/m								
Loblolly pine	0	0	0	0	0	0	0	0	0
	36	0	0	0	0	0.1	0.3	0	0
	64	0.8	0.9	0.2	0.4	0	0	0	0
	80	2.0	1.8	0.2	0.4	0	0	0	0
	98	2.9	1.4	0.6	0.5	0	0	0.1	0.3
Water oak	0	0	0	0	0	0.1[d]	0.3	0.1[d]	0.3
	36	2.2	1.3	1.3	1.2	0.2	0.4	0.4	0.5
	64	4.0	0	3.2	1.1	2.4	1.4	2.1	1.5
	80	4.0	0	4.0	0	4.0	0	3.3	0.8
	98	4.0	0	4.0	0	3.9	0.3	3.4	1.1
Sweetgum	0	0	0	0	0	0	0	0.3[d]	0.9
	36	2.2	1.4	1.5	1.4	0.5	0.7	0.1	0.3
	64	3.8	0.6	3.4	1.0	2.2	1.0	2.1	1.1
	80	4.0	0	4.0	0	4.0	0	3.5	1.0
	98	4.0	0	4.0	0	3.7	0.9	3.7	0.7

[a] Pine mean was significantly different from hardwood means at the 0.05 level, according to Duncan's multiple range test.

[b] Means from the lower three intensity levels were significantly different from each other and from the 80 and 98 kJ/s/m levels at the 0.05 level, according to Duncan's multiple range test.

[c] Means for dgl class = 3 cm and dgl class = 5 cm were significantly different from each other and from the two larger dgl classes at the 0.05 level of significance, according to Duncan's multiple range test.

[d] Trees scarred by agents other than fire.

Table 6. Percent mortality and percent girdled as of May 1986, within each species x diameter class x intensity cell (n = 10), after burning at 5 intensities with the propane-fueled fire simulator.

Species	Fire intensity	------Ground-line diameter class (cm)------ 3		5		7		9	
		Dead	Girdled	Dead	Girdled	Dead	Girdled	Dead	Girdled
	kJ/s/m								
Loblolly pine	0	0	0	0	0	0	0	0	0
	36	0	0	0	0	0	0	0	0
	64	0	0	0	0	0	0	0	0
	80	40	40	0	0	0	0	0	0
	98	60	60	0	0	0	0	0	0
Water oak	0	0	0	0	0	0	0	0	0
	36	20	30	0	10	0	0	0	0
	64	100	100	10	60	10	40	0	30
	80	100	100	50	100	10	100	0	50
	98	100	100	80	100	40	90	10	70
Sweetgum	0	0	0	0	0	0	0	0	0
	36	0	30	0	10	0	0	0	0
	64	90	90	20	60	0	10	0	10
	80	100	100	80	100	50	100	10	70
	98	100	100	70	100	50	90	20	80

Table 7. Analysis of variance of girdling data[a] for 600 trees treated at five levels of intensity with the propane-fueled fire simulator.

Source of variation	D. F.	S. S.	M. S.	E. M. S.[b]	F	P
Species (S)	2	2.496	1.248	$e + q_1(S)$	25.86	0.0001
DGL class (D)	3	0.699	0.233	$e + q_2(D)$	4.83	0.0050
Intensity (I)	4	4.533	1.133	$e + q_3(I)$	23.47	0.0001
Error (e)	50	2.414	0.048	e		
Total	59	10.142				

[a] Data are from species x dgl class x intensity cells, n = 10, and represent the fraction of trees in a cell girdled by the burning treatments.

[b] e = error variance; $q_1(S)$ = fixed species effect; $q_2(D)$ = fixed dgl class effect; $q_3(I)$ = fixed intensity effect.

The scarring pattern in the present study is opposite that reported for natural fires and simulated fires (Hare 1965b, Gill 1974), where the highest temperatures and first scars occur on the leeward side of stems. Either our thermocouples were placed too near the ground to measure maximum leeward temperatures or the temperature distributions in our simulated fires were different from those in natural fires.

Crown Scorch. Crown scorch occurred on 36% of the loblolly pine trees treated, and though the crown heating produced by the fire simulator does not approximate that found in natural fires, scorch varied with diameter class and fire intensity in predictable ways in this study (Figure 10). Percent of the crown scorched was negatively related to tree height and positively related to Byram fire intensity, though these two variables together only explained 28% ($P = 0.0001$) of the variation in scorch percent. Ambient temperature was unrelated to scorch percent in this study, though it has been cited as a major factor in crown scorch encountered in other studies (Villarrubia and Chambers 1978, Cooper and Altobellis 1969). Air temperature might have been more important had we burned under warmer conditions, or if radiant energy from a long flame front had been available to affect the upper crowns of our experimental trees.

Basal Sprouts. Fire injury to tree stems often induces basal sprouting. In this study, 84% of girdled sweetgum trees and 95% of girdled water oak trees produced sprouts from the stem below the girdle or from the root crown. For sweetgum the percentage of trees sprouting depended significantly on dgl class, with the smallest trees sprouting most frequently (Figure 11). The regression equation for the

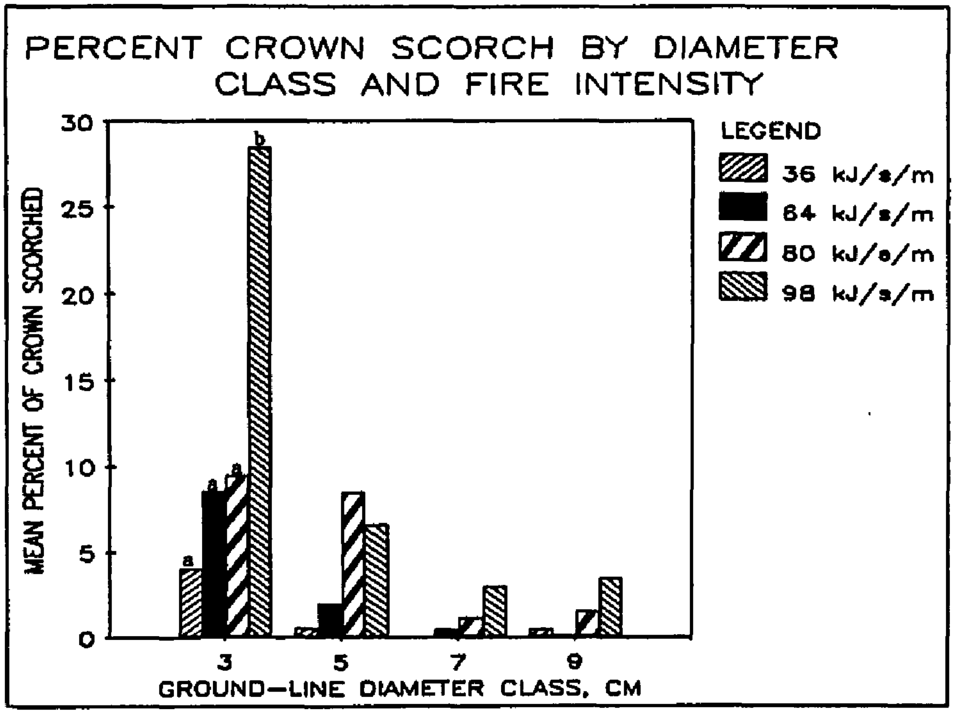

Figure 10. Mean percent crown scorch of 160 loblolly pine trees as a function of tree diameter for four fire intensities after treatment with the propane-fueled fire simulator. Means in the 3 cm dgl class designated by the same letter are not significantly different at the 0.05 level according to Duncan's multiple range test. Intensity had no significant effects on percent scorch within the 5, 7, or 9 cm dgl classes. Overall mean for the 3 cm dgl class was significantly different from those of the other dgl classes at the 0.05 level.

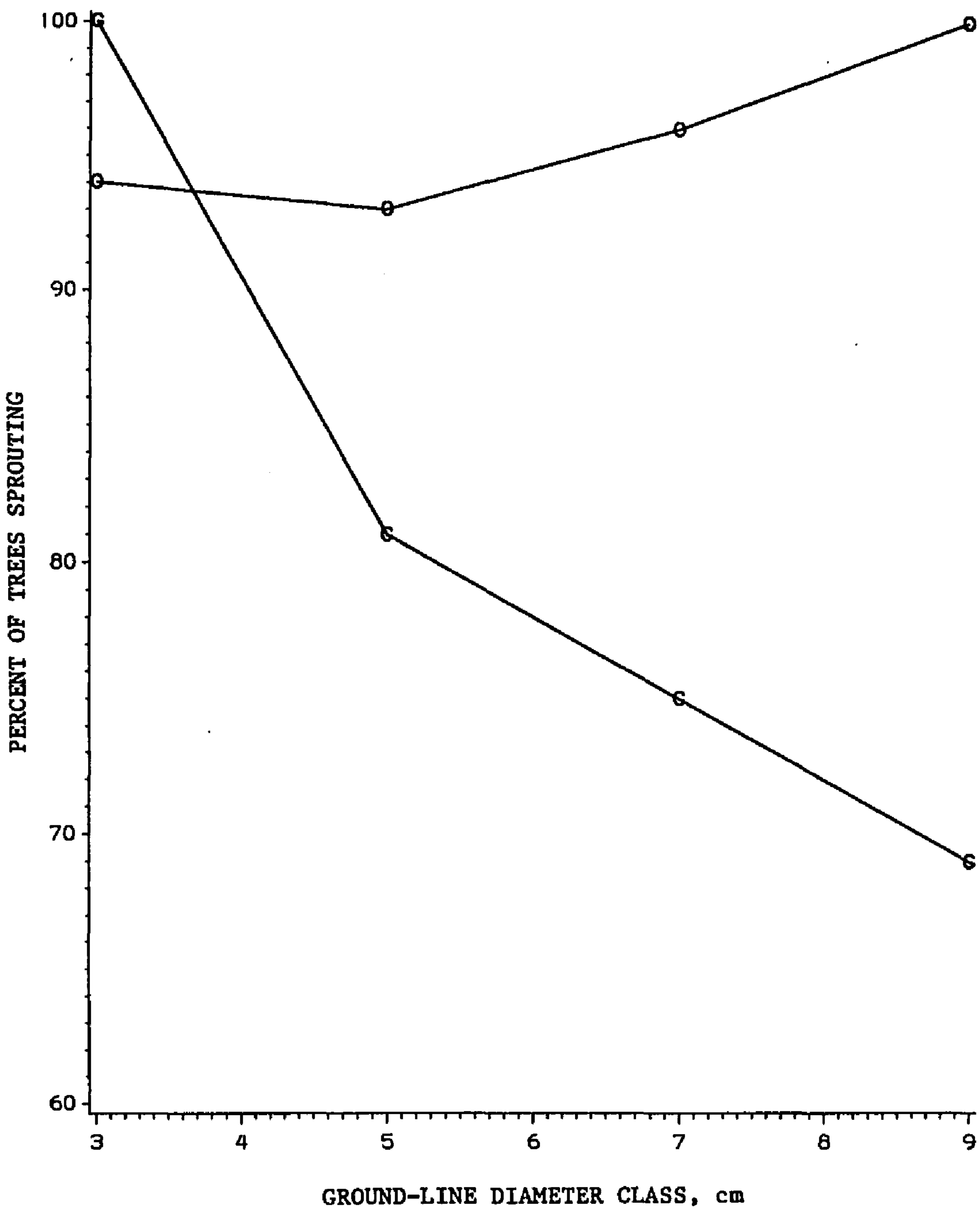

Figure 11. Percent sprouting of girdled water oak (O) and sweetgum (G) saplings 13 months after treatment with the propane-fueled fire simulator.

relationship is

$$S = 1.114 - 0.050\ (D) \qquad \text{(eq. 3)}$$

$$\text{model alpha} = 0.04,\ r^2 = .92$$

where S = the proportion of trees sprouting in a diameter class, and

D = ground-line diameter class, cm.

No such relationship was evident for water oak (Figure 11).

Negative relationships between diameter and sprouting ability have been documented before (e.g. Elliott and Pomeroy 1948, Putnam et al. 1960). The inverse linear relationship between sweetgum diameter and sprouting ability may be a result of age-related processes, or it may result from environmental factors affecting large and small trees differently.

Mortality. Stems which are girdled will die unless the girdle is narrow enough for callus tissue to close the gap and reestablish phloem connections across the wound (Noel 1970). However, girdled trees often take months or even years to die because xylem connections remain intact and the immediate needs of the portion of the stem distal to the girdle for water and inorganic nutrients can still be met (Noel 1970, Stone 1974).

As of May 1986, 60% of the girdled trees in this study (54% of the girdled water oaks, 62% of the girdled sweetgums, and all of the girdled loblolly pines) had died (no living cambium distal to the girdle) (Table 6). All dead trees in the study had been girdled by fire. Most of the remaining girdled trees exhibited symptoms of poor vigor including chlorosis, leaf abscission, abnormally small leaves, greatly reduced shoot elongation, and dieback of portions of the crown. Decay-causing fungi were invading the exposed wood in the girdle wounds.

I recognized three distinct patterns of mortality among the girdled stems. Some trees, notably small trees which were treated with a high intensity fire, wilted 1-2 days after treatment and died within 10 days. Rapid death of these trees indicates that xylem tissue was probably damaged by the flames, causing water stress above the girdle.

Most of the trees which had died by May 1986 exhibited a second pattern of mortality, in which the tree lived several weeks to several months, while gradually beginning to exhibit the symptoms described above. Many of the trees produced leaves in the spring of 1986, having survived 13 months after being girdled. Eventually I expect these trees to lose their leaves and/or turn brown and die, possibly as a result of decay of the xylem in the region of the girdle, or possibly as a result of decline of the root system due to the restricted availability of photosynthates from the shoot. However, in August 1986 many girdled trees were still alive.

The third mortality pattern was exhibited by live, girdled trees which broke off at the girdle during windstorms. This mechanism was rare in the first 12 months but became more common as the trees entered their second year after the treatments, and as the wood under the girdles became more thoroughly decayed. This pattern has, as of August 1986, been almost entirely restricted to sweetgum trees, but a few oaks are now reaching the point where they could also blow down.

Possible causes for the longevity of girdled trees observed in the study are: 1) presence of large, healthy root systems with large reserves of photosynthates at the time of burning, 2) partial replenishing of root carbohydrate reserves by basal sprouts after girdle formation, and 3) natural root connections with other, nongirdled trees of the same species. Though the relative importance of these three mechanisms is open to question, all three were probably operating. The third hypothesis seems especially likely because most of the hardwoods in the study were of sprout origin and had extensive root connections, many of which were obvious to the aboveground observer. Stone (1974) reported on red pines which survived girdling for several years because natural root grafts provided photosynthates to root systems of girdled trees.

Growth. First-year mean diameter and height growth for the 397 nongirdled trees in this study are presented in Tables 8 and 9. SAS General Linear Models procedure (SAS Institute 1985 p. 433-506) was used to evaluate the effects of several variables on first-year diameter growth of the nongirdled trees in the study. Only the dbh or tree height at the time of burning (all species) and the degree to which the tree was scarred (pine only) significantly affected diameter growth the following year. Therefore the degree of scarring was pooled with the error term for sweetgum and water oak. Initial height was not as good a predictor of dbh growth as was initial dbh; therefore dbh was used in the models. The analyses are presented in Table 10. Similar models for height growth followed the same general patterns as those for dbh growth and are therefore omitted from this discussion.

Table 8. Diameter growth at breast height (mm), for 397 nongirdled trees of three species in four ground-line diameter classes treated at five fire intensity levels with the propane-fueled fire simulator.

Species	Intensity	Ground-line diameter class (cm) 3		5		7		9	
		mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
	kJ/s/m								
Loblolly pine	0	17	5	18	5	18	4	20	4
	36	16	5	18	7	18	4	21	6
	64	14	3	15	2	17	4	18	4
	80	17	6	19	4	17	6	19	7
	98	9	4	17	4	17	5	21	6
Water oak	0	5	4	9	3	8	3	12	6
	36	6	3	6	3	10	3	15	6
	64	--[a]	--	7	4	9	3	8	3
	80	--	--	--	--	4	--	11	5
	98	--	--	--	--	--	--	9	3
Sweetgum	0	4	2	7	6	8	5	9	5
	36	6	3	6	4	5	4	9	3
	64	-2[b]	--	8	6	6	5	7	3
	80	--	--	--	--	15	--	9	5
	98	--	--	--	--	--	--	12	8

[a] Missing values resulted from all of the trees in the cell being girdled.

[b] Negative value from one tree, due to measurement error or damage to bark at measurement point.

Table 9. Height growth (cm), for 397 nongirdled trees of three species in four ground-line diameter classes treated with five fire intensity levels with the propane-fueled fire simulator.

Species	Fire intensity	Ground-line diameter class (cm) 3		5		7		9	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
	kJ/s/m								
Loblolly pine	0	98	27	111	31	114	36	123	26
	36	97	24	115	25	115	22	124	24
	64	79	24	104	18	126	27	119	19
	80	97	26	101	29	110	15	118	24
	98	64	18	106	32	106	29	121	20
Water oak	0	69	34	71	31	89	36	74	30
	36	43	26	68	31	99	20	119	39
	64	--[a]	--	67	27	99	31	81	46
	80	--	--	--	--	--	--	55	44
	98	--	--	--	--	15	--	77	42
Sweetgum	0	32	29	61	39	73	30	56	36
	36	45	24	49	27	56	30	79	30
	64	43	--	59	30	68	30	50	33
	80	--	--	--	--	91	--	72	29
	98	--	--	--	--	--	--	69	11

[a] Missing values resulted from all trees in the cell being girdled.

Table 10. Analysis of variance of first-year dbh growth of loblolly pine, water oak and sweetgum saplings as a function of initial dbh or initial dbh + degree of scarring after treatment with five levels of fire intensity with the propane-fueled fire simulator.

Species	Source	D.F.	Seq. SS	M.S.	F	P
Loblolly pine	Dbh	1	306.18	306.18	12.35	0.0006
	Scar degree	2	134.92	67.46	2.72	0.0684
	Error	186	4610.39	24.79		
	Total	189	5051.49			
Water oak	Dbh	1	483.69	483.69	29.45	0.0001
	Error	100	1642.39	16.42		
	Total	101	2126.08			
Sweetgum	Dbh	1	231.47	231.47	13.33	0.0004
	Error	103	1787.92	17.36		
	Total	104	2019.39			

I then modeled pine dbh growth as a function of dbh and degree of scarring (DS), with dbh as a covariable, in order to determine if separate slopes or intercepts resulted between different values of DS. Separate slopes would indicate the presence of a significant interaction between dbh and DS, meaning that the dbh growth was affected differently by initial diameter depending on the degree of scarring. Separate intercepts would indicate that DS had a significant effect on dbh growth which was constant across dbh. No significant differences were evident between the intercepts (DS) or the slopes (DS x dbh interaction) at the 95% confidence level. However, the effect of DS on pine growth was significant at alpha = 0.0696. I therefore pooled the interaction (slope) term with error but left the DS (intercept) term in the pine model, since the probability of significance is too large to justify pooling. Analysis of covariance of the pine dbh growth model is presented in Table 10.

Dbh growth models are presented in Table 11. The pine model contains DS as a covariate; estimates given are additive adjustment factors for the intercept term for deriving separate lines for each value of DS. Since the dbh * DS interaction term was nonsignificant, all of the lines are assumed to have the same slope. No pines were scarred on three sides, and girdled (DS = 4) trees were omitted, so the model only includes estimates for DS = 0, 1, 2.

The R^2 value for the sweetgum dbh growth model was 0.115, while that for the water oak dbh growth model was 0.228. The R^2 for the loblolly pine model was only 0.087. With R^2 values as low as these, the models are not useful for prediction. However, they serve to illustrate

Table 11. Regression models of first post-burn year dbh growth of nongirdled loblolly pine, water oak and sweetgum saplings treated with the propane-fueled fire simulator.

Species	Parameter	Estimate	Student's t statistic to test H_o: Parameter=0	P>0	Standard Error of Estimate	Model R^2
Loblolly pine	intercept	9.42421	3.75	0.0002	2.5104	0.0873
	dbh	0.05415	2.56	0.0113	0.0212	
	DS = 0[a]	5.95566	2.29	0.0232	2.6011	
	DS = 1	5.06732	1.86	0.0649	2.7292	
	DS = 2	0.0	--	--	--	
Water oak	intercept	2.835069	2.40	0.0182	1.181	0.2275
	dbh	0.146911	5.43	0.0001	0.02707	
Sweetgum	intercept	2.899573	2.49	0.0142	1.162	0.1146
	dbh	0.097809	3.65	0.0004	0.02678	

[a] DS = degree of scarring.

the importance of initial diameter in growth models and the relative unimportance of fire effects short of girdling on growth. Apparently other factors (for example, those related to microsite) which were not measured in this study accounted for much of the observed variation in dbh growth in the first post-burn year.

Logistic Models

Equations. The single best combination of variables for predicting girdling probability of all three species proved to be dgl and mean temperature exposure (mte). The models are:

Loblolly Pine

$$P_p = [1 + e^{-(5.1302 - 0.4361(dgl) + 0.00021(mte))}]^{-1} \quad \text{(eq. 4)}$$

Water Oak

$$P_o = (1 + e^{-(-0.9480 - 0.0653(dgl) + 0.00019(mte))})^{-1} \quad \text{(eq. 5)}$$

Sweetgum

$$P_g = (1 + e^{-(-2.3597 - 0.0901(dgl) + 0.00030(mte))})^{-1} \quad \text{(eq. 6)}$$

Units for dgl are mm; those for mte are $^{o}C*s$. Three-dimensional representations of these models and the data from which they were derived are presented in Figures 12-17. The smooth curves (Figures 12, 14, and 16) represent predicted probabilities, while the scatter diagrams (Figures 13, 15, and 17) depict the actual girdling data.

Model statistics are presented in Table 12. The chi square statistic is given by $(\text{Beta/Std. err.})^2$, and is used to test the null hypothesis H_o: Beta = 0, where Beta is the model parameter. The R^2 statistic is analogous to a coefficient of multiple determination but is adjusted to compensate for the number of parameters estimated for the model. The likelihood ratio statistic (Table 13) is a measure of goodness of fit for the model (SAS Institute, Inc. 1983 p. 182-202).

Diagnostics. In order to determine the validity of the model assumptions, I tested each data set with the SAS procedure EMPTREND (empirical trend plot) as described by Harrell and Lee (1985). EMPTREND output includes mean values of model variables within user-selected quantiles and graphs of these means against the Y-variable and/or against the logit of the Y-variable. EMPTREND output for each of the three girdle models is presented in Figures 18-23. In all cases, strong relationships were evident between predictor variables and both the proportion of stems girdled in the quantiles (P) and the logit of P, indicating that the basic assumption of logistic models, equation 2 (page 31), is valid for these data.

Applications. These models can be used to predict the probability of girdling of loblolly pines, water oaks, and sweetgums from 2.6 to 10.0 cm ground-line diameter in a fire of a given temperature exposure

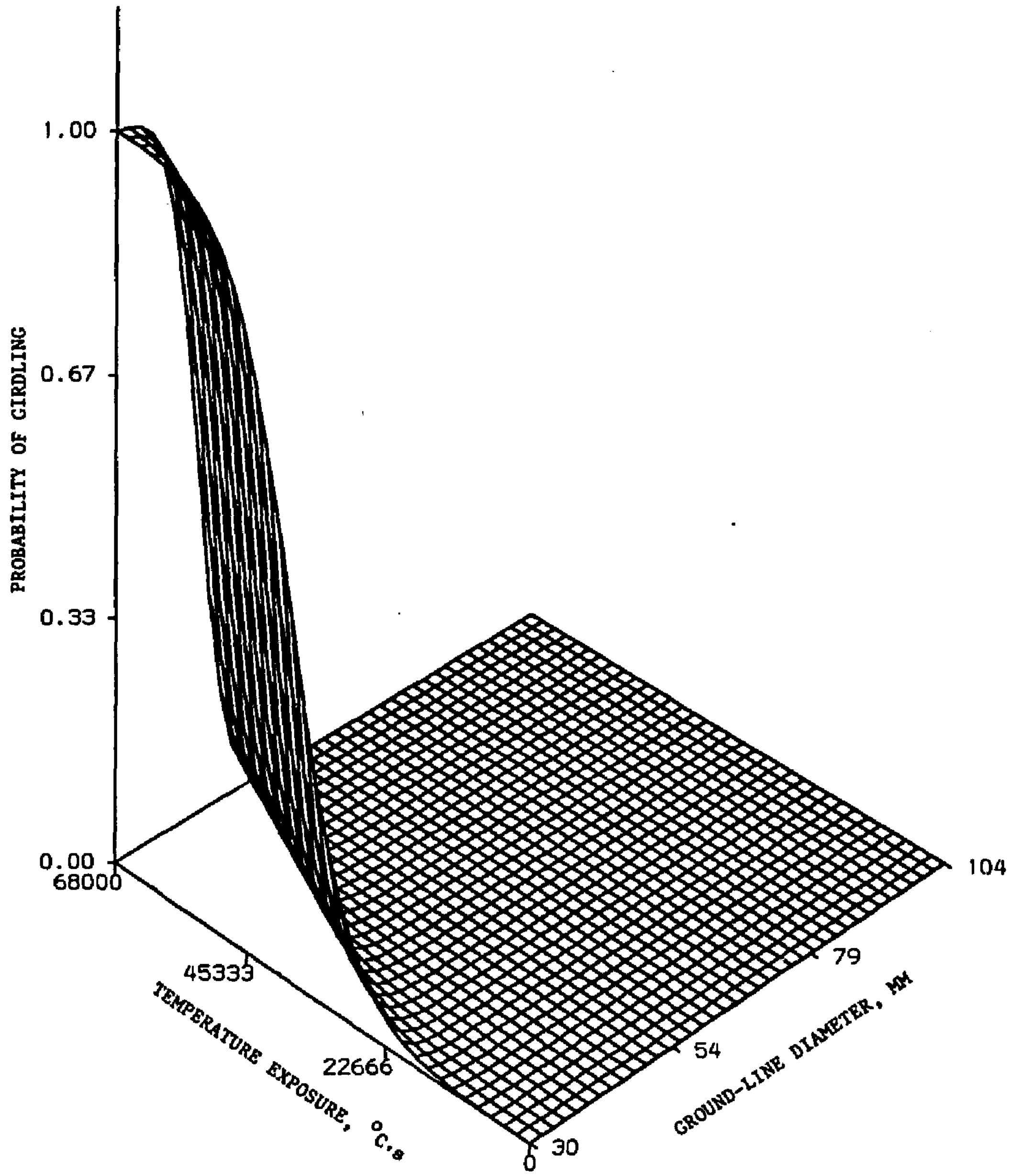

Figure 12. Predicted girdling probability based on data from 200 loblolly pine trees between 3 and 10 cm dgl treated with the propane-fueled fire simulator.

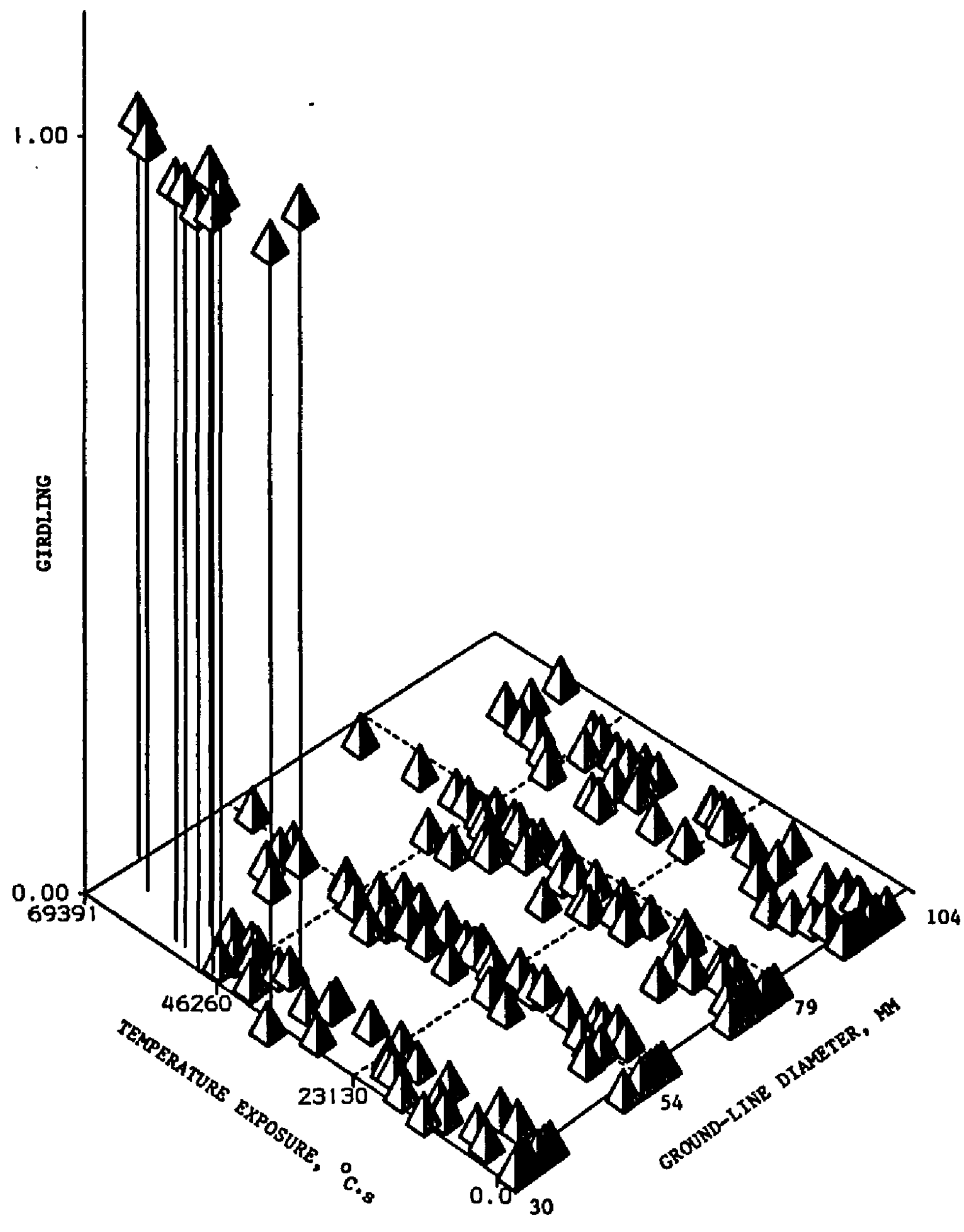

Figure 13. Girdling as a function of dgl and mte for 200 loblolly pine trees treated with the propane-fueled fire simulator.

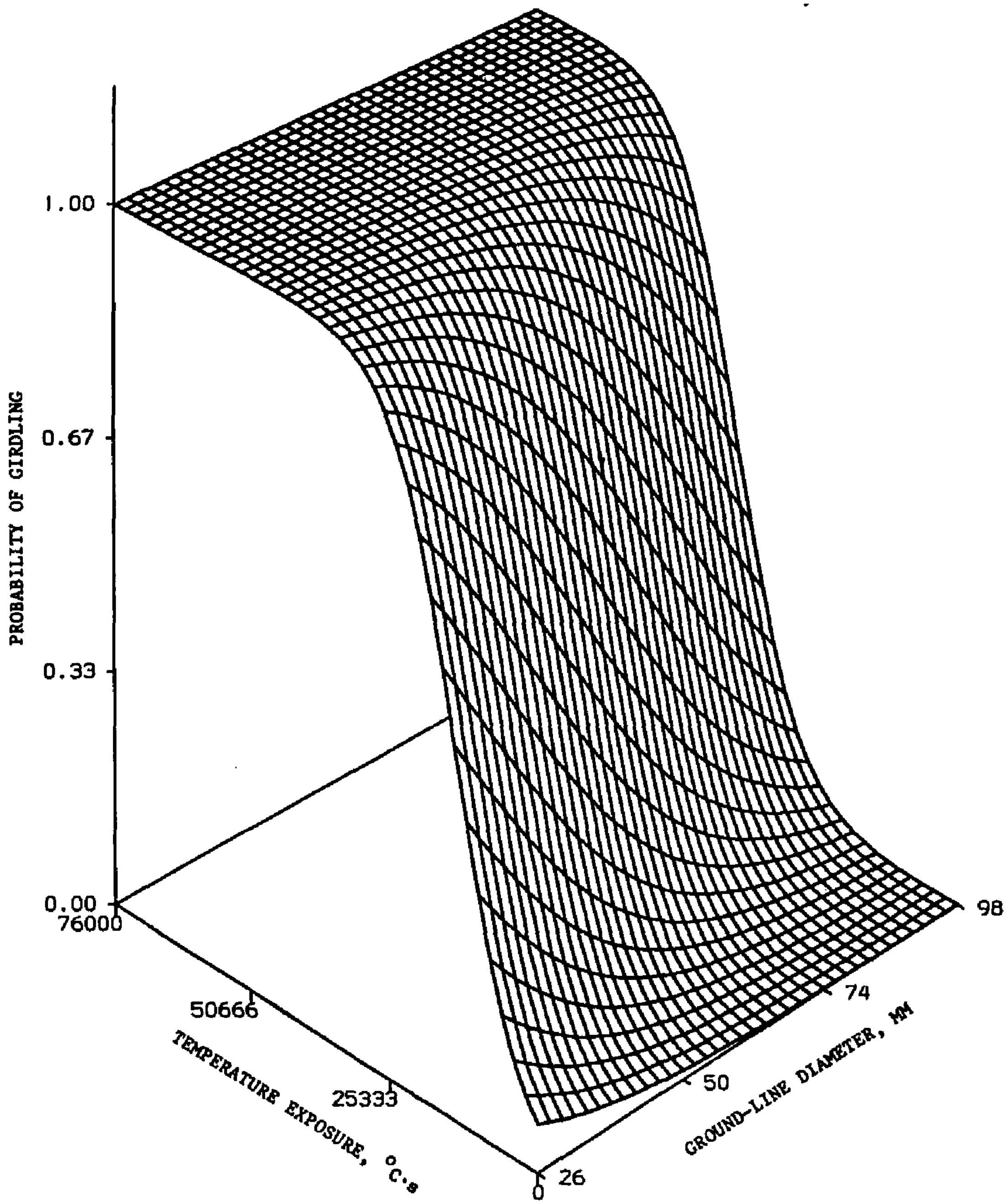

Figure 14. Predicted girdling probability based on data from 200 water oak trees between 2.6 and 9.5 cm dgl treated with the propane-fueled fire simulator.

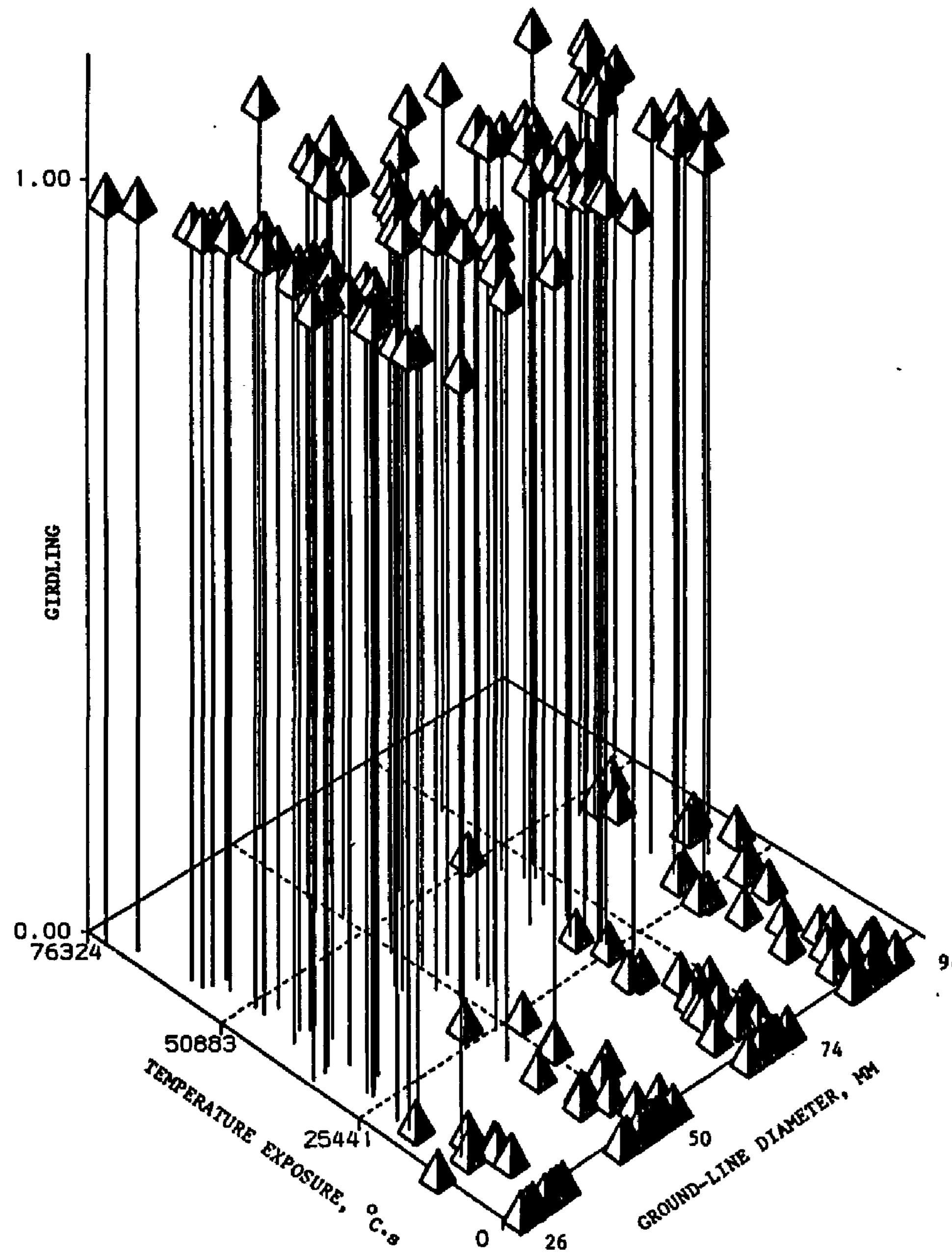

Figure 15. Girdling as a function of dgl and mte for 200 water oak trees treated with the propane-fueled fire simulator.

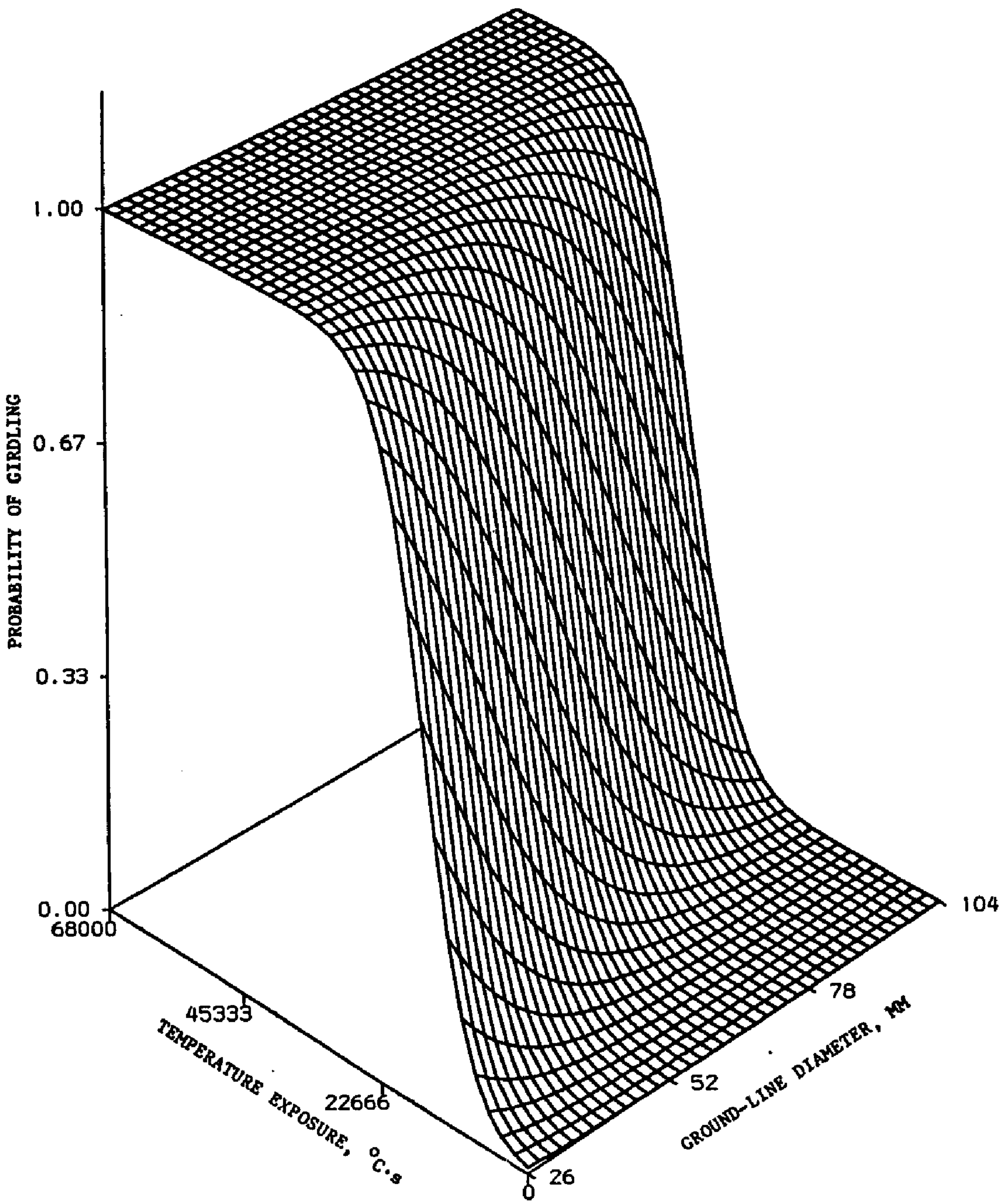

Figure 16. Predicted girdling probability based on data from 200 sweetgum trees between 2.6 and 10 cm dgl treated with the propane-fueled fire simulator.

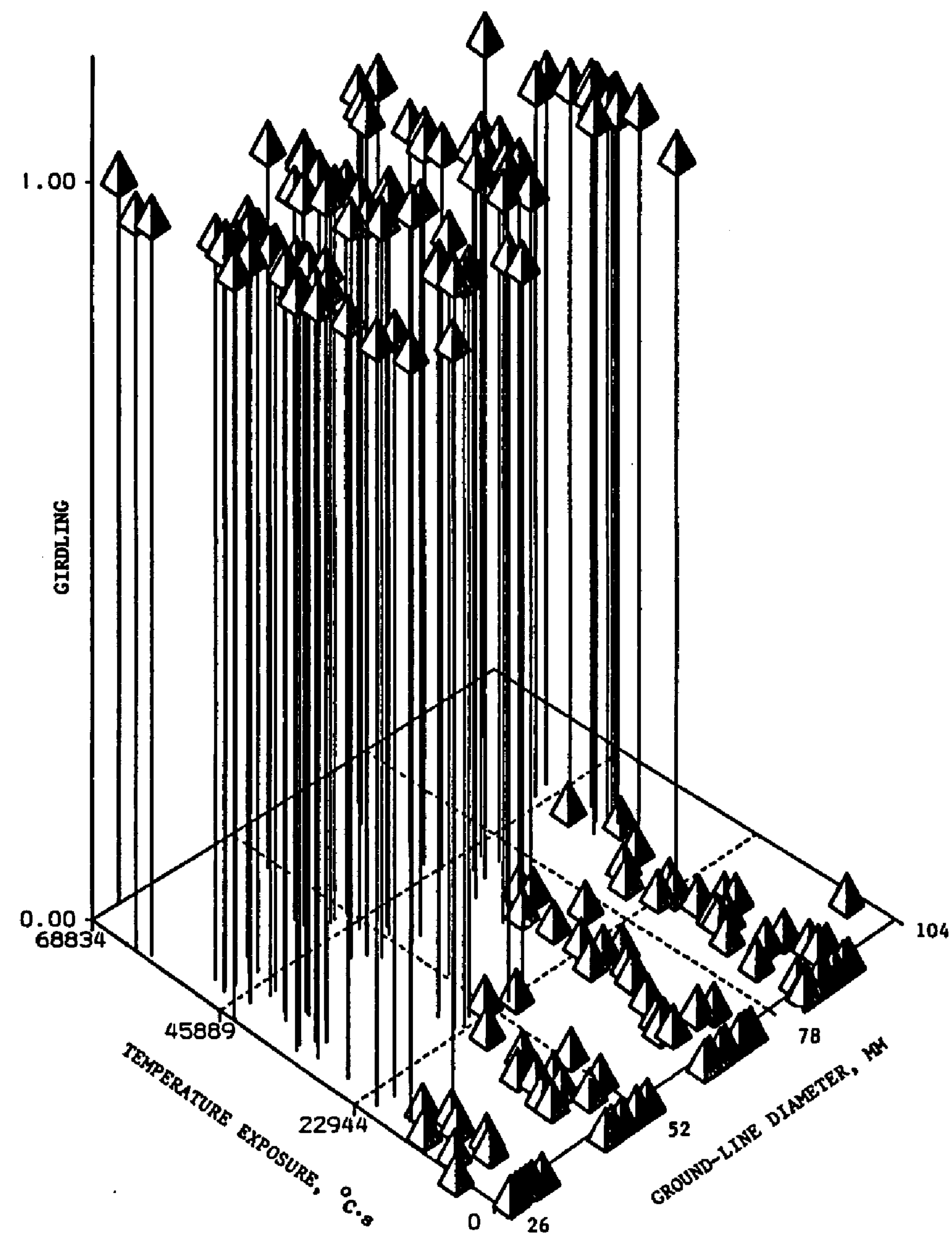

Figure 17. Girdling as a function of dgl and mte for 200 sweetgum trees treated with the propane-fueled fire simulator.

Table 12. Parameters and statistics for three logistic models of probability of girdling of loblolly pine, water oak and sweetgum saplings in simulated fire conditions produced by the propane-fueled fire simulator.

Species	Variable	Beta	Standard error	Chi-square	P $(X^2>0)$	Model R^2
Lob. pine	Intercept	5.1302	5.9679	0.74	0.3900	0.701
	Dgl	-0.4361	0.1869	5.45	0.0196	
	Mte	0.00021	0.00008	6.05	0.0139	
Water oak	Intercept	-0.9480	0.8191	1.34	0.2471	0.646
	Dgl	-0.0653	0.0151	18.70	0.0000	
	Mte	0.00019	0.00003	45.63	0.0000	
Sweet-gum	Intercept	-2.3597	0.9943	5.63	0.0176	0.748
	Dgl	-0.0901	0.0234	14.85	0.0001	
	Mte	0.00030	0.00006	28.42	0.0000	

Table 13. Likelihood ratio statistics (LRS)[a] for logistic models of probability of girdling of loblolly pine, water oak, and sweetgum saplings in simulated fire conditions.

Species	D. F.	Model LRS	P
Loblolly pine	2	59.61	<0.0001
Water oak	2	183.32	<0.0001
Sweetgum	2	211.28	<0.0001

[a] The LRS is a chi-square statistic which represents the amount of variation explained by the model. It is analogous to the model sum of squares in standard regression models.

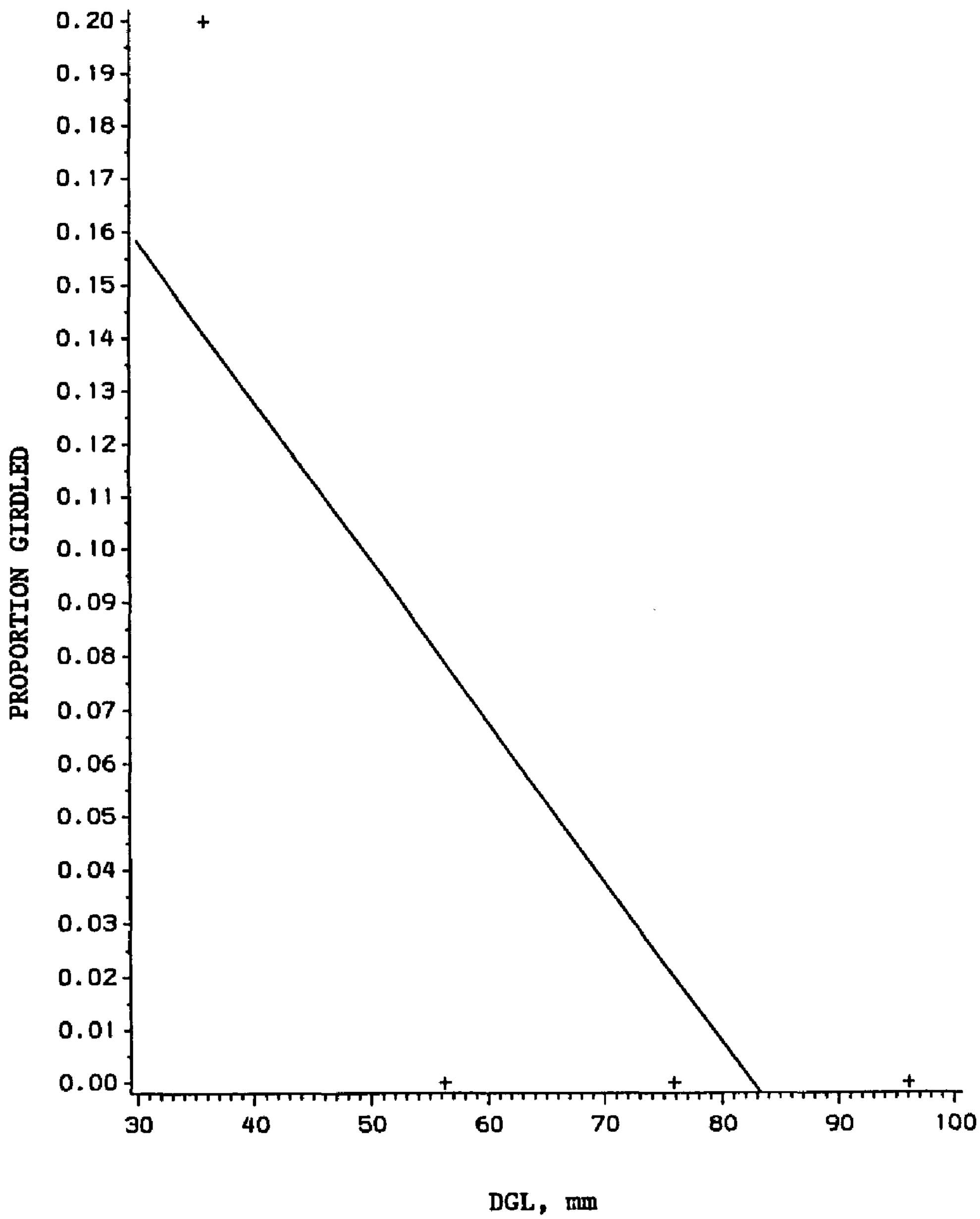

Figure 18. Loblolly pine percent girdled, averaged across temperature exposures, as a function of ground-line diameter class after treatment with the propane-fueled fire simulator.

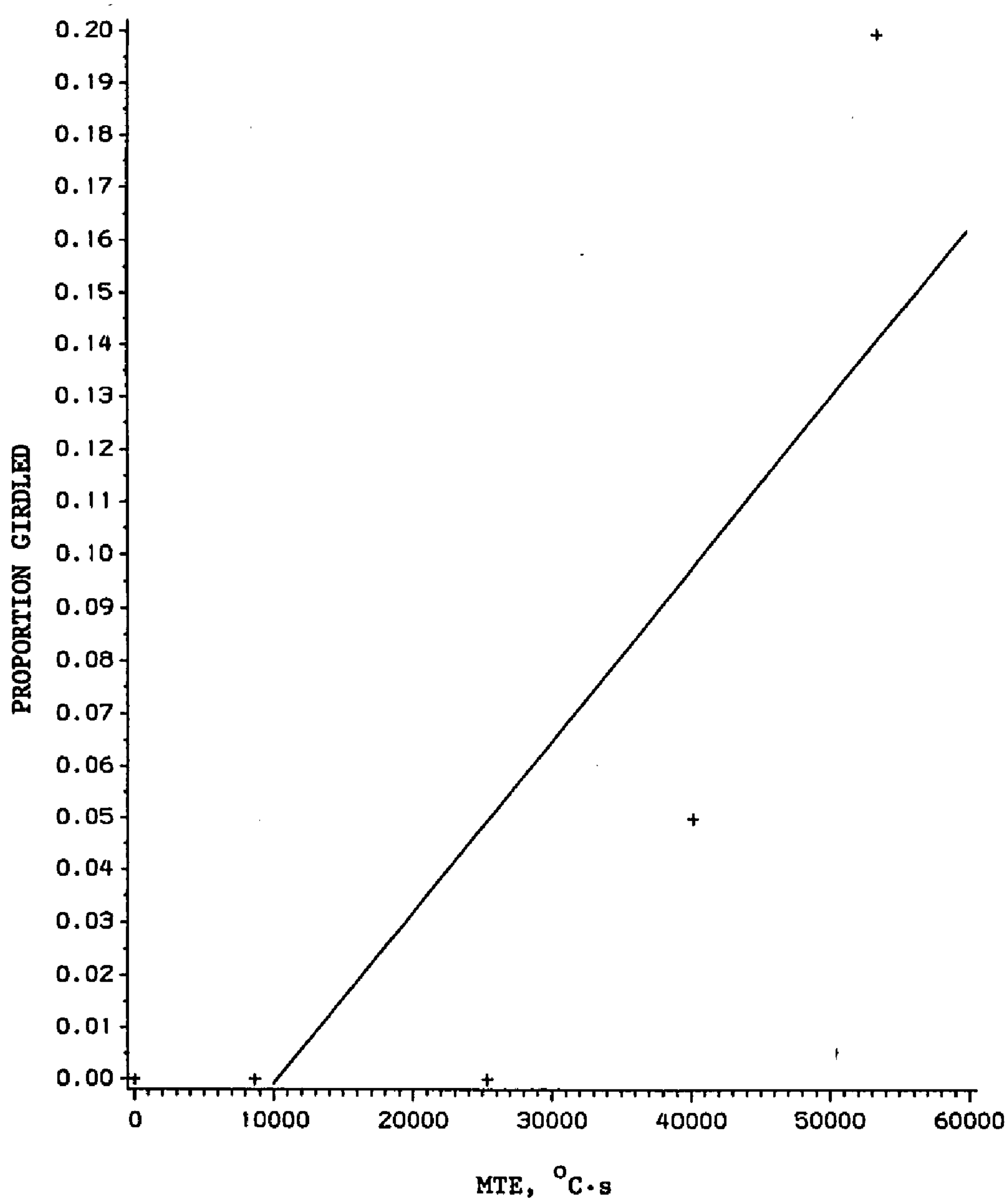

Figure 19. Loblolly pine percent girdled, averaged across diameters, as a function of mean temperature exposure during treatment with the propane-fueled fire simulator.

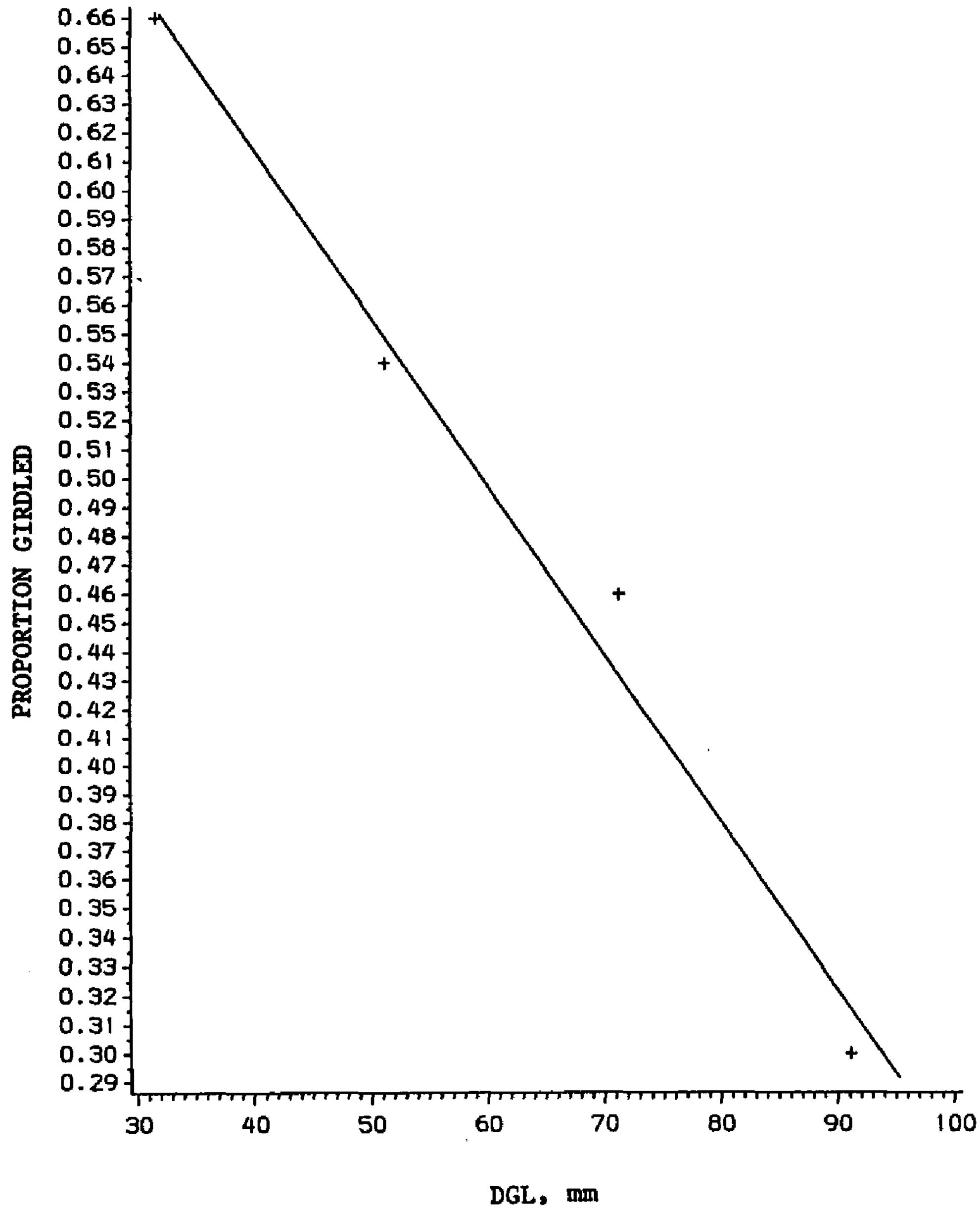

Figure 20. Water oak percent girdled, averaged across temperature exposures, as a function of ground-line diameter class after treatment with the propane-fueled fire simulator.

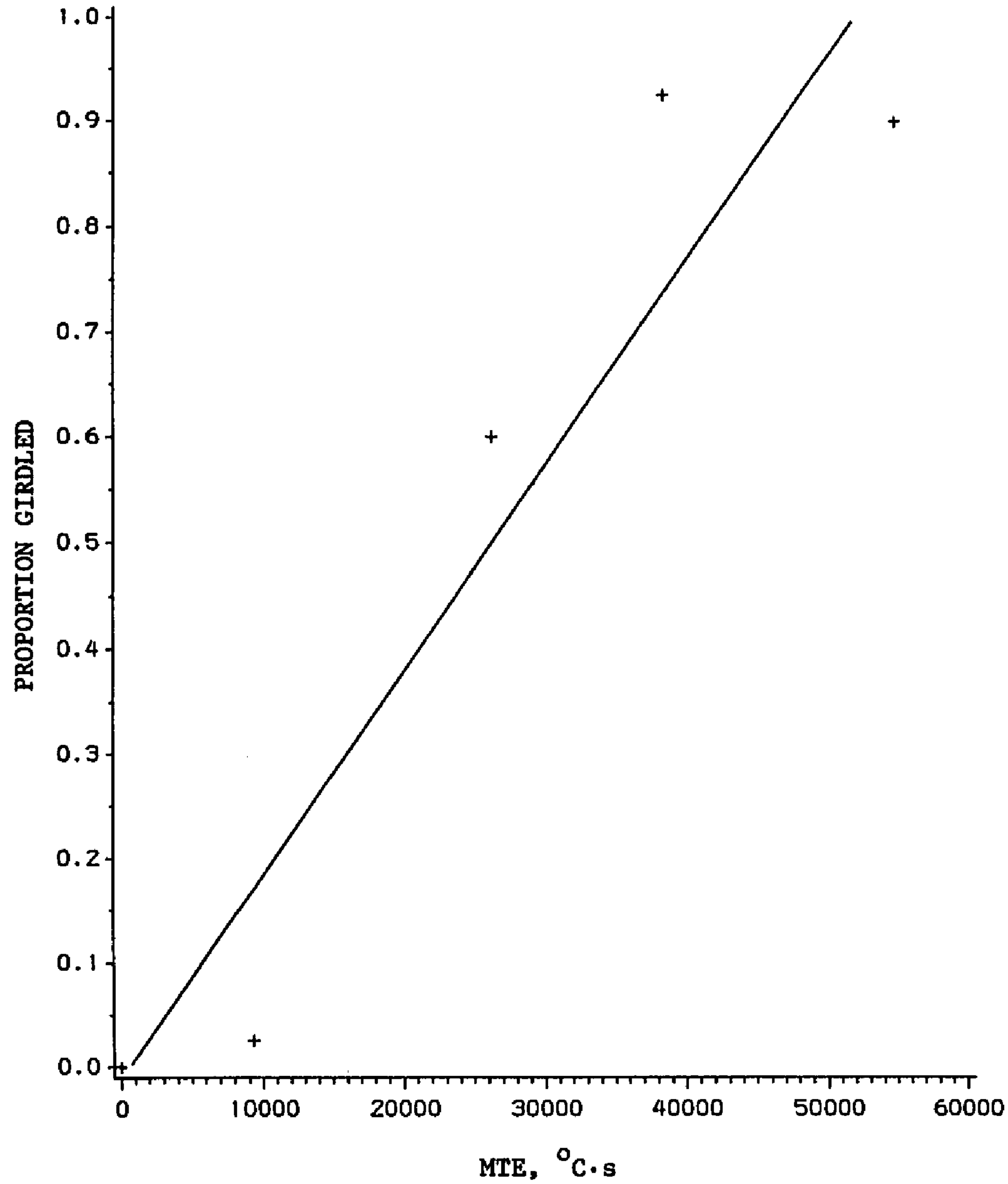

Figure 21. Water oak percent girdled, averaged across diameters, as a function of mean temperature exposure during treatment with the propane-fueled fire simulator.

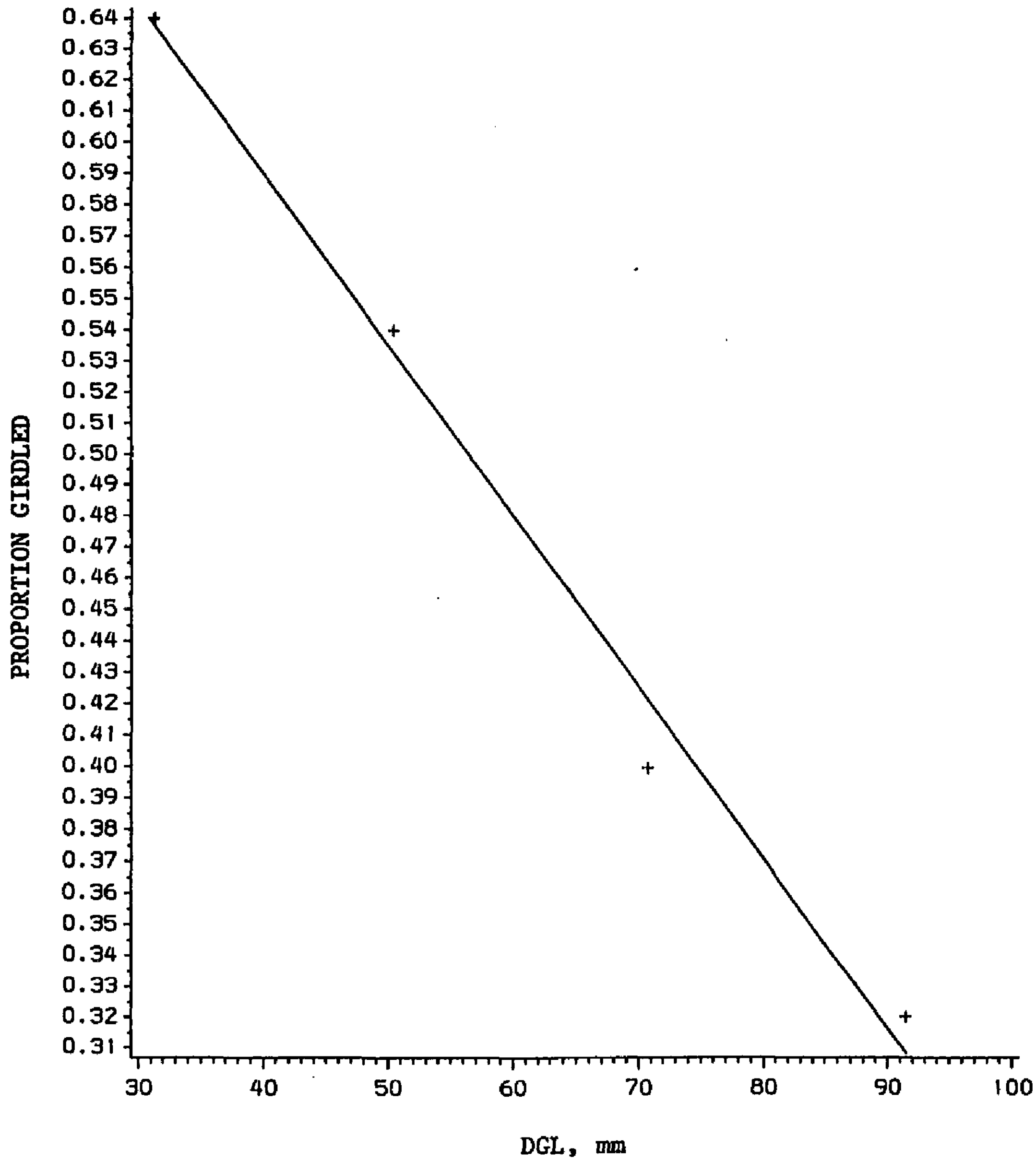

Figure 22. Sweetgum percent girdled, averaged across temperature exposures, as a function of ground-line diameter class after treatment with the propane-fueled fire simulator.

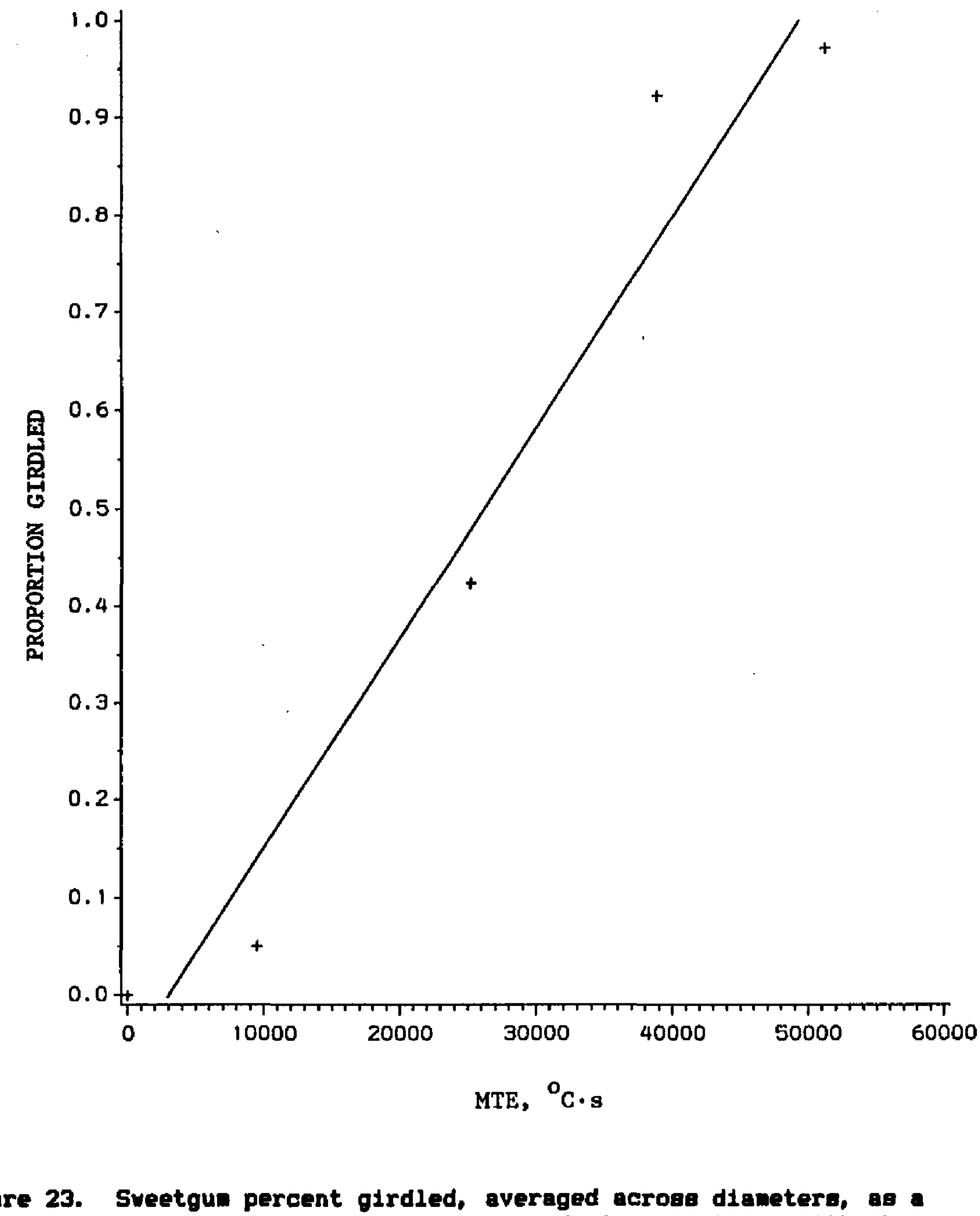

Figure 23. Sweetgum percent girdled, averaged across diameters, as a function of mean temperature exposure during treatment with the propane-fueled fire simulator.

below 70,000 kJ/s/m. The models can identify the smallest diameter pines which may be safely burned with a fire of a given intensity, and they can likewise be used to decide whether a fire of a given intensity will be effective in controlling water oaks and sweetgums within given diameter ranges. The safety and efficacy of burning young stands with various pine/hardwood diameter ratios can thus be determined.

Operational assumptions for applying these models are:

1. stands are burned with an early spring backfire under relatively uniform wind and fuel conditions;
2. crown scorch is not severe enough to cause pine mortality or serious growth reductions;
3. girdling a stem results in eventual death of tissues distal to the injury, so that the girdling probability approximates the probability of mortality;
4. the probability of a single stem being girdled may be equated to the proportion of a population of stems of the same dgl which will be girdled;
5. the temperature exposure may be selected with reasonable accuracy and consistency by choosing the proper environmental conditions for burning.

The first assumption is necessary because the model is based on the response of individual stems, and thus the pyric microenvironments around the bases of all the trees in the stand must be similar, or at least vary in some predictable pattern. For example, small areas dominated by hardwoods will probably have less intense fires than pine-dominated areas under the same atmospheric conditions (Williamson and Black 1981). For accurate prediction of hardwood response in these areas, it would be necessary to use the actual temperature exposure values which occur there, not an overall mean for the stand.

Since the pine model does not include a term to incorporate the effect of crown scorch, its effect must be assumed to be negligible. Operationally, this means that the response of pines to fires which would cause serious scorch (high intensity and/or low wind speed) cannot be predicted by the present model, because mortality would result from causes other than stem girdling.

The third and fourth assumptions deal with the practical applications of the models. They are not necessary if we simply wish to predict the probability of girdling of single stems, but most users will wish to predict mortality percent in stands and so must assume that probability of girdling will equal percent mortality.

The final assumption presently imposes serious limitations on the practical application of the models, since the science of prescribing fires of given intensities is in its infancy, notwithstanding long experience with the art of prescribed burning in the southeastern United States. Before these models can be used for fire intensity selection, a set of prescriptions must be developed which allow relatively close control over temperature exposure.

SUMMARY AND CONCLUSIONS

Summary of Methods

Six hundred saplings of three species in four dgl classes were treated at five approximate levels of fire intensity, 0, 36, 64, 80, and 98 kJ/s/m, with a propane-fueled backfire simulator during February-April 1985. Girdling, scarring and first-year dbh and height growth were measured. The following variables were measured and tested for inclusion in logistic regression models of probability of girdling: temperature exposure (area under the curve of temperature * time with a baseline of 60°C) at four locations around the base of the tree, maximum temperature near the bark surface at four locations around the base of the tree, duration of lethal temperatures at four locations around the base of the tree, dgl, dbh, bark thickness, bark moisture content, air temperature, bark temperature before burning, and relative humidity.

Summary of Results

Fire parameters. Temperature exposure means (across species, dgl, and replication) varied from 4,960°C*s for the leeward thermocouple in the least intense flame setting to 60,460°C*s for the windward thermocouple in the most intense flame. The mean temperature exposure across the four thermocouple positions on an individual tree (mte) varied from 0 to 76,324°C*s. Mean temperature maxima varied from 139 to 718°C. Individual temperature maxima were as high as 923°C on the windward side. Mean duration of lethal temperatures varied between 141 and 275 s.

Plant responses. Scarring and girdling response of the trees in this study were as follows:

Species	Percent scarred	Percent girdled
Loblolly pine	18	5
Water oak	72	49
Sweetgum	71	48

Thirty-six percent of the treated pines had some degree of crown discoloration (scorch). Scarring had little or no effect on diameter or height growth of nongirdled trees. In May 1986, 13 months after the end of the treatment period, 60% of the girdled trees had died and the remaining girdled trees were displaying symptoms such as chlorosis, slow growth, and abnormal leaf development. Eighty-four percent of the girdled sweetgum trees had sprouted from below the fire injury; 95% of the girdled water oaks had done so.

Girdling probability models. A logistic model was developed for each species to predict the probability of girdling of a tree of a given dgl subjected to a fire of known mean temperature exposure. Values of R^2 varied from 0.646 to 0.748 for the three models. Loblolly pines between 3 and 10 cm dgl appear to be substantially more resistant to surface fires than water oak or sweetgum saplings in the same size range. Loblolly pines greater than 5 cm dgl may safely be burned at all fire temperature exposures tested, provided that excessive crown scorch is avoided. Moreover, mean temperature exposures greater than 50,000^{o}C*s are almost certain to girdle water oaks and sweetgums less than 10 cm dgl, while temperature exposures between 40,000 and 50,000^{o}C*s will girdle most water oaks and sweetgums in that size range.

Conclusions

I have drawn the following conclusions from this study.

1. Stands of loblolly pines in which enough trees have attained a dgl of 5 cm so that full stocking is assured may be safely burned at a mean temperature exposure of 40,000 to 70,000°C*s, which corresponds roughly to a fireline intensity of 80 to 100 kJ/s/m. This range of temperature exposures or intensities will be effective in girdling most water oak and sweetgum stems between 2.6 and 10.0 cm.

2. Fire scars which did not encircle the stem had little or no negative effect on the first-year diameter or height growth of trees of the species and sizes studied. Thus, no short-term (first-year) reduction of hardwood competition would appear to result from a prescribed fire unless stems are girdled.

3. The benefits of girdling water oak and sweetgum saplings are largely limited to top removal, since 95% and 84%, respectively, of the trees of those species in this study produced basal sprouts in response to girdling.

Further Research Needs

One of the characteristics of scientific studies seems to be that they raise more questions than they answer. The questions raised in the present study suggest at least four potentially fruitful avenues of investigation.

1. The models presented herein need to be tested in natural fire conditions; that is, temperature exposures should be measured in natural prescribed fires and used with the models I have developed to predict girdling. I am currently conducting such a study.

2. Prescriptions which specify temperature exposures or fireline intensities need to be developed for southern pine fuels so that the models may be put to practical use.

3. Similar models need to be developed for other species so that managers faced with diverse forest flora can more accurately predict the results of prescribed fires.

4. The efficacy of top removal as a competition control measure in young stands needs to be evaluated. The flush of vigorous sprouts which followed girdling of most of the hardwoods in this study suggests that burning, by increasing the number of stems, may exacerbate the competition problem instead of alleviating it, especially if prescribed burning is not carried out on a regular basis.

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APPENDIX A

Description of the propane-fueled surface fire simulator.

The fire simulator (Figure 24) operated by moving a pair of propane burning elements past the base of a tree by means of a track system and threaded 1.26-cm-diameter rods. Power was supplied by a 1/3 hp, 1725 rpm electric motor mounted on a lawnmower frame. A dual 15-cm diameter "squirrel cage" fan provided wind, and a 3000W gasoline-powered generator provided 110V power in the field.

The 19-liter propane tank which contained fuel for the flame rested on the back of a lawnmower frame during operation. A double-gauge pressure regulator, with hose pressure gauge calibrated from 0-30 psi (0-2.1 kg/cm^2), metered propane to a "Y" coupling, which split the gas into two 5 m by 0.64 cm inside diameter rubber fuel hoses leading to propane jets (1.22 mm orifice, #55). Valves were placed below the "Y" coupling and immediately above the jet on each hose for ease of shut-off. A fuel-type "quick disconnect" joint provided for easy removal of the jet assembly from the hose. The jets were permanently mounted in the ends of steel, gas-furnace burning elements which were modified by closing the part of the slot opening closest to the jet and by cutting additional slots in the end of the element. They produced a 56-cm-wide flame front, or 28 cm on each element. Gas-air mixture was adjusted at the jet end of the burner. Burning elements were mounted upside-down (flames pointed down) on moving rods attached to the tracks.

Two tracks supported and moved the burning elements. Each track consisted of two, 2.1-m garage door guides (C-shaped in cross section) bolted at each end to an 11.5-cm piece of angle-iron so that the guide grooves faced each other 6.4 cm apart. Between the guides, we mounted a 2.1-m long, 1.26-cm diameter threaded steel rod in pillow-block bearings

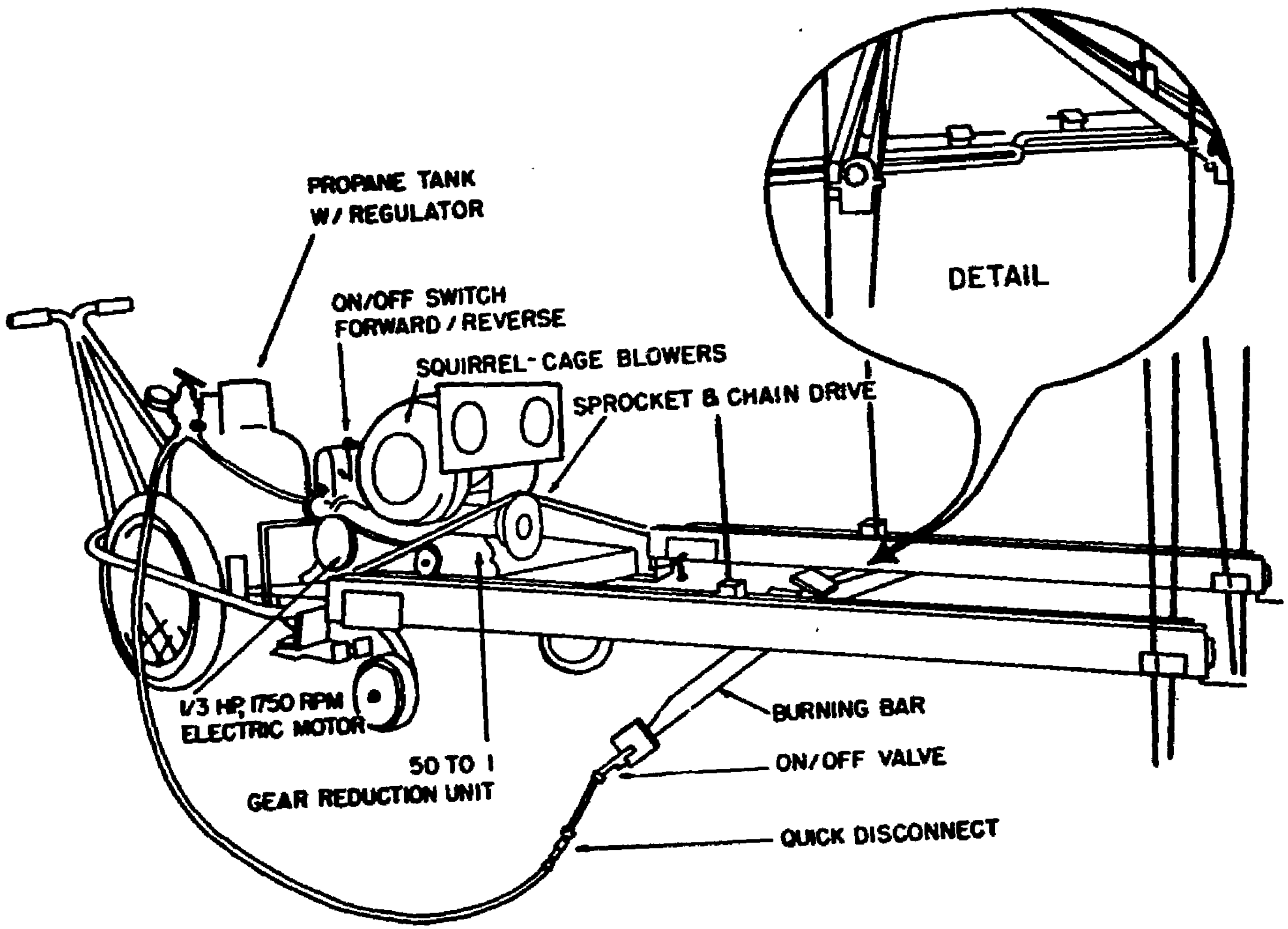

Figure 24. The propane-fueled surface fire simulator. (Figure originally published by Greene et al. 1986; used by permission of Society of American Foresters.)

bolted to the angle-iron. Five-cm sprockets on each end of the threaded rods allowed the rods to be rotated by a chain drive. Short (6 x 10 cm) metal tabs at each end of each track fit into slots on the mover frame, providing a means of quick attachment and removal of tracks. Each track was supported by four adjustable, 0.95-cm diameter, 76-cm long steel legs secured in metal sleeves by thumbscrews. The sleeves were welded to the tracks.

The support structure for the burning elements was a rectangular steel tube 10 cm long and 5 x 5 cm in cross section. A 1.26-cm threaded nut was welded on the tube so that as the threaded rod turned, the steel tube moved along the rod. Fifteen-cm steel runners welded to both sides of the rectangular tube fit into the garage door guides and prevented rotation of the support structure. A 0.95-cm diameter smooth steel rod, bent at a 90^{o} angle so that it extended 30 cm horizontally and 40 cm vertically, supported the burning element. A thumbscrew mounting on the rectangular steel tube provided for vertical adjustment of the burning element; the element slid freely on the horizontal portion of the rod providing horizontal adjustment. In operation, the tracks extended forward from the lawnmower frame parallel to each other and 86 cm apart, and the burning elements pointed inward (towards each other) so that they touched at the ends. Two operators were required to slide the burning elements back as they passed the tree bole. The tracks were reversible, so that after a run they could be turned around, avoiding the time-consuming process of backing the elements along the tracks.

Power to turn the threaded rods was supplied by a 1/3 hp reversible electric motor mounted on the lawnmower frame. A belt and pulleys (10 cm to 5 cm) transferred the motion of the motor to a 50:1 gear box; the gear box turned an 11.4-cm diameter sprocket, which drove a chain and turned both rods by means of sprockets mounted on their ends. Our machine moved the burning elements at 0.56 cm/s, an average rate of spread for backfires in southern pine fuels (McNab 1977, Davis and Martin 1960, Crow and Shilling 1983). This rate could be adjusted by changing sprocket and pulley diameters.

Wind was simulated with a dual 15-cm diameter "squirrel cage" fan mounted atop the gearbox. Our fan provided a 9 km/h wind at ground level at the base of the tree (1.5 m from the fan). By reversing motor direction, the burning elements could be moved toward the fan to simulate a backfire or away from it to simulate a headfire. We blocked natural wind by staking tarpaulins around the entire apparatus, allowing operation on moderately windy (< 15 km/h) days.

The fire simulator was wired so that separate switches controlled the fan and motor and a third switch controlled motor direction. All wiring was enclosed in metal conduit to prevent damage to wires in field operation. The device was connected to the generator via a heavy-duty 15-m extension cord.

VITA

Thomas Alexander Greene was born July 29, 1958, in Corpus Christi, Texas, to Mary and George Greene. He graduated from Barbers Hill High School, Mont Belvieu, Texas, in 1976 and earned his B. S. in botany (1980) and M. S. in range science (1983) at Texas A&M University.

He married Anita Gale Dugat May 19, 1978, and has, to date, sired no children. He is currently a candidate for the degree of Doctor of Philosophy in the School of Forestry, Wildlife, and Fisheries, Louisiana State University.

DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Thomas Alexander Greene

Major Field: Forestry

Title of Dissertation: Mortality and Growth Responses of Juvenile Pines and Hardwoods to various Fire Intensities

Approved:

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Date of Examination:

February 27, 1987